THE VREDEFORT MOUNTAIN LAND IN THE SOUTHERN TRANSVAAL AND THE NORTHERN ORANGE FREE STATE

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From a survey made by Mr. L. T. NEL.

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XXXVII. .... Second Sheet.
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XXXIX. .... Sketch-map of the boss of alkali-granite and the dykes of nepheline-syenite on Schurvedraai and Koedoeslaagte. From a survey made by Mr. L. T. NEL.

THE GEOLOGICAL MAP.

The topography of the geological map accompanying this Memoir is based on the Potchefstroom (1917) and Kroonstad (1903) Degree Sheets; these are official maps published by the Surveyor Generals respectively of the Transvaal and the Orange Free State on the scale of 1000 Cape Roods to the inch, which is very nearly equivalent to one in 150.000. Use was also made of the Vredefort (1908), Viljoen's Drift (1908) and Heilbron (1909) Military Reconnaissance Sheets published by the Geographical Section, General Staff, War Office, on the scale of one in 125,000.

The Degree Sheets are compiled from the surveys of the individual farms and consequently have a considerable degree of accuracy as far as the position of villages, homesteads, river-courses etc. are concerned. They, however, show the relief of the ground either not at all or in a very unsatisfactory way. Contour-lines are not used. The boundaries of the farms, on the contrary, are given rather accurately. These boundaries can be found in the field by the position of the corner-beacons and not seldom by barb-wire fences connecting those beacons. Not rarely the original farms, shown on the map, are subdivided in smaller portions or subfarms which may all be fenced in, and in that case the usefulness of the map is lessened. The absence of reliable data on the relief of the ground makes these maps of very little value for geological detail work.

The farms are distinguished on these topographical maps, and also on the geological map accompanying this memoir, by their names and their numbers, e.g. Rietpoort 649, Witbank 166 etc. In the text of this memoir the names only are given, save in those instances where two farms happen to have the same name; then the numbers are added as e.g. Rietfontein 555 and Rietfontein 664, Klipfontein 343 and Klipfontein 70.

The altitudes of several spots are given on this geological map in meters ; they are taken from the War Office Maps referred to, i.e. Sheets Vredefort, Viljoen's Drift and Heilbron. These maps have contour-lines and, from the topographical point of view, are distinctly superior to the Degree Sheets. Unfortunately the names, numbers and boundaries of the farms are not given on the former, which makes them almost useless for geological work, except where the relief of the ground makes an exact orientation possible.

The geological survey-work on which the geology given on the map is based is enumerated on the map-sheet itself.

PREFACE.

In the year 1922 a Shaler Memorial Fund Expedition of Harvard University, organized by Prof. DALY, visited South Africa with the main object to study the igneous phenomena of the Bushveld in the Transvaal. The expedition consisted of Professors DALY and PALACHE of Harvard University and Prof. MOLENGRAAFF of the Technische Hoogeschool at Delft, and was joined by Dr. F. E. WRIGHT on behalf of the Geophysical Laboratory of the Carnegie Institution of Washington. It was decided to study, besides the igneous problem of the Bushveld, also individually other geological problems in South Africa which might be considered exceptionally attractive. Thus one of the members, Prof. MOLENGRAAFF, who during visits to some portions of the Vredefort Mountain Land, in 1890, 1898 and 1903, had realised the singularly fascinating geological problems of that area, resolved to put its study on his program, and had the good fortune to find an enthusiastic collaborator in Dr. A. L. HALL, the Assistant Director of the Geological Survey of the Union of South Africa.

The following memoir is the result of their joint work. The authors spent the month of March, some days in April and the greater part of July 1922 in the field. The analyses were made in Johannesburg, the map was constructed in Pretoria and the greater portion of the microscopical examination of the rocks was carried out in Delft. The courtesy of the Director, Dr. A. W. ROGERS, and the desinterestedness of Mr. L. T. NEL, M. Sc., geologist, who mapped a great portion of the Vredefort area in 1923 and 1924, have enabled the writers to incorporate some of the results obtained by the official survey, in the geological map and sketches accompanying this memoir.

The writers take this opportunity of recording their great indebtedness to Mr. H. G. WEALL F. I. C. Government Chemical Laboratories, Johannesburg, who made eighteen analyses specially for this paper, and thus enabled the chemical aspects of all the more important rock-groups to be illustrated. They are equally indebted to Dr. P. KRUIZINGA, Conservator at the Geological Museum in Delft, who prepared the majority of the microphotographs and to Mr. T. MEYER, of the Division of Veterinary Research, for similar assistance. Their thanks are also due to Prof. J. A. GRUTTERINK M. E. Director of the Petrological Laboratory at Delft and Mr. J. DE VRIES, M. E. Conservator at the same Institute, with whom one of them had the opportunity of discussing several petrological questions.

Dr. A. W. ROGERS, Mr. L. T. NEL and Dr. F. E. WRIGHT gave permission to reproduce some of their photographs.

The authors were fortunate in being able to discuss some of the problems in the field with Prof. DALY and Dr. F. E. WRIGHT, who paid a short visit to the Vredefort country in April 1922.

Pretoria / *Delft*, April 1925.

CHAPTER I.

Review of Previous Researches and Statement of the Problem.

About 120 km. south-south-west of Johannesburg the imposing stretch of hills and ranges known as the Vredefort Mountain Land terminates the monotonous landscape of the northern Orange Free State and at once arrests the attention by its striking topography as well as by its intricate geology. All round the village of Vredefort extends an almost circular boss of granite with some gneiss and schists, about 40 km. in diameter ; a third of this area is covered by younger rocks of lower Karroo age. Where covered by these, the granite forms perfectly flat country ; where it is uncovered, the surface is gently undulating — here and there relieved by a low hillock or by small patches of rocky ground.

This granite-boss is surrounded by a belt of sediments composed of ranges of prominent and often picturesque hills, all trending parallel with the outer margin of the granite and together forming a gigantic amphitheatre or girdle, about 16 km. wide, completely encircling the granite.

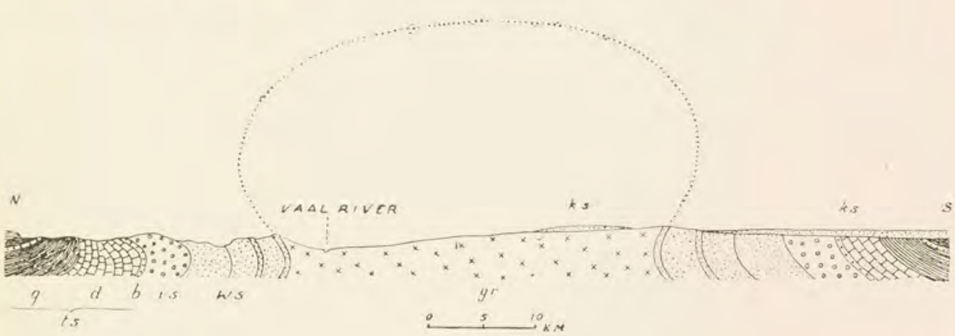

Fig. 1.

Ideal Section across the Vredefort area and its encircling girdle of overtilted sediments. The shape of the dome indicated by the dotted line is entirely speculative.

gr. Vredefort granite ; *ws.* Witwatersrand System ; *vs.* Ventersdorp System ; *ts.* Transvaal System ; *b.* Black Reef Series ; *d.* Dolomite Series ; *g.* Gatsrand Beds or Pretoria Series ; *ks.* Karroo System.

The sedimentary complex of this girdle ranges from the Lower Witwatersrand Beds up to the Pretoria or Gatsrand Beds in apparently conformable succession (see Fig. 1).

All round the granite the beds are tilted at a high angle or overtilted, the Lower Witwatersrand Beds in most places dipping towards the granite. This overtilting continues for miles along the periphery of the granite and, since it affects thousands of yards of thickness, it has led to an inversion of the stratigraphical succession ; this result is the most striking tectonic problem of the Vredefort Mountain Land. Near the granite the sediments are highly metamorphosed, the entire boss being encircled by a belt of altered sediments.

As far as we know the earliest record of the occurrence of granite in the Vredefort area is found in DUNN's [1]) Geological sketch-map of South-Africa of the year 1887.

The village of Vredefort is indicated on this map as situated on a slightly curved belt of granite well south of the Vaal River trending in an east-west direction and only touching the Vaal River near the mouth of the Mooi River at its western limit and again near the mouth of the Klip River at its eastern limit.

This belt of granite is shown to be sandwiched in between two tracts of schists, taken as belonging to the Namaqualand schists. On SCHENCK'S map [2]) of the year 1888 no granite is marked, the entire area being coloured as belonging to the Table Mountain Sandstone.

In the year 1891 MOLENGRAAFF [3]) published a paper on the goldfields of the Western Transvaal, including the so called Vaal River Goldfields in the Vredefort area, in which he incorporated briefly the geological results of a joint visit paid to the western and central portions of the Vredefort area by DRAPER and himself. They recognised the circular form of the boss of granite and gneissic granite with the belts of basic schists in it and saw the boss partly covered by much younger, horizontal beds of the coal bearing portion of the Karroo System. They found the belt of sediments encircling the granite-boss to be composed of beds ranging from the lowest Witwatersrand up to the Gatsrand (Witwatersrand Beds, Klipriver-amygdaloid and porphyrite, Black Reef, Dolomite and Gatsrand Beds). They observed the tilting and overtilting of the strata round the granite and looked upon diastrophism as the cause of these disturbances, taking the granite-boss as the core of a gigantic denuded dome or anticlinorium. They regarded the Vredefort Granite as older than the sediments and correlated it with the granite of the area west of Klerksdorp and with the granite of the boss north of Johannesburg.

In the same year ROBINSON [4]) — then Government Mine Inspector — gave an account of the Orange Free State goldfields. Taking a large pan

1) E. J. DUNN. **21**.
2) A. SCHENCK. **84**.
3) G. A. F. MOLENGRAAFF. **57**.
4) H. A. ROBINSON. **70**.

called the Inland Sea on the farm Klipkraal 529 as the centre of the entire area, he gives a brief description of the granite, gneiss and schists of the central boss. ROBINSON enumerates in some detail the ridges composed of sedimentary rocks, which encircle the basement rocks. He follows in his description of the various formations as much as possible the order adopted for the South African formations by GREEN [1]).

In the same year 1891 PENNING [2]) published a paper on the geology of the Southern Transvaal, in which no details are given on the Vredefort area. On the accompanying map, however, the circular Vredefort boss is shown partly covered by Karroo Beds (his High Veld Beds) and encircled first by a dolerite belt, then by a girdle of Witwatersrand Beds and further by dolerites and rocks of the Klipriver Series (= Gatsrand Series).

GIBSON [3]), in the year 1892, mentions gneisses, schists, granites and gabbros from the low hummocky ground near the village of Vredefort. He briefly describes a belt of quartzites and shales with here and there a thin conglomerate band, from a point west of Vredefort, which belt stretches round the granite as far as Lindequesfontein, a distance roughly estimated at 16 km. He mentions the vertical or nearly vertical position of the beds and identifies the whole series with the quartzite and shale group lying beneath the Main Reef in the Witwatersrand. In a diagram and section illustrating the general structure of the country west of Vredefort, he shows the belt of sediments to be thrusted against and over the Vredefort granite-boss.

In 1894 MOLENGRAAFF [4]) published more in detail the results of the observations made conjointly with DRAPER. On the map and sections accompanying this paper the so-called Witwatersrand basin is represented as a large curved trough, separated from the anticlinal area of the Witwatersrand on its northern limit and from the anticlinal dome of Vredefort at its southern side by a system of parallel strike-faults, separating the granite from the encircling belt of sediments and again marking off large groups of sediments in this belt one from the other.

Although accepting SCHENCK's conception of the existence of large folds in the Witwatersrand area, MOLENGRAAFF surmises faulting to be more the determining factor in the structure of the Witwatersrand basin than folding. He mentions the occurrence of a belt of actinolite-schist along the periphery of the boss, which is, however, not shown on the accompanying sketch-map. On that map for the first time the outlines of a great portion of the Vredefort granite-boss are represented.

DRAPER [1]) in the year 1894 published a section through the Vredefort

1) A. H. GREEN. **24**.
2) W. H. PENNING. **65**.
3) W. GIBSON. **22**.
4) G. A. F. MOLENGRAAFF. **58**.
5) D. DRAPER. **19**.

area, based on the above mentioned observations made in 1890. He omitted quite rightly the system of faults shown in MOLENGRAAFF'S section round the Vredefort granite-boss and he marked in this section a zone of igneous rocks between the granite and the girdle of sediments.

BUNKELL [1]) in 1896 published a paper on the Venterskroon gold fields. Although this paper was sharply criticised when it was read, yet the section (Vol. XII, Pl. VI) accompanying it is far the best section of the Vredefort area until then published. It shows the Vredefort Granite as the oldest or basement rock. Between it and the encircling sediments a basaltic rock is shown partly intrusive in the granite. Both the Lower and the Upper Witwatersrand Beds and the intercalated basaltic rocks are shown in considerable detail and at the surface in an overtilted position. The "amygdaloid dolerite" (now Ventersdorp Beds) in this section unconformably overlies the Upper Witwatersrand Beds.

HATCH [2]) two years later published the results of a survey of the Witwatersrand and other districts in the southern Transvaal, also comprising the Vredefort area. HATCH considers the Vredefort Granite with its accompanying schists to belong to the oldest rocks of the Transvaal, his Archaean rocks, and thus to form the floor of all other sediments. He is of opinion that the Witwatersrand basin was formed by trough-faulting, but that lateral thrust is responsible for the Witwatersrand Beds being sharply turned up on edge near their outcrop. He is of opinion that in the Venterskroon district the normal succession of the Cape System (now Transvaal System), Ventersdorp System and Witwatersrand System is reversed and explains this inverted sequence by accepting the existence of a series of parallel strike faults, along which each successive older series has been thrust up and over the younger beds. He takes the fault-planes to be marked by vast outpourings of igneous rocks, which probably followed closely on the dynamic disturbances.

On the accompanying map, which is also separately [3]) published, and in the sections this conception is demonstrated in detail. A belt of igneous rocks is shown between the granite and the sediments just as in the sections of DRAPER and BUNKELL and for the first time on this map two small granite bosses are marked, detached from the main Vredefort boss well within the area occupied by the Lower Witwatersrand Beds, one on the farm Brakfontein and one or two on the farm Koedoeslaagte.

In the year 1896 DRAPER [4]) emphasized the occurrence of two great anticlines in the Witwatersrand area, "of which the granite at Vredefort "and that at Half-Way House (between Johannesburg and Pretoria) re-"present the axes". He advocates the intrusive character of the granite,

1) H. B. BUNKELL. **12**.
2) F. H. HATCH. **34**.
3) F. H. HATCH. **35**.
4) D. DRAPER. **20**.

saying : "while this great earthmovement was in progress the centre portion "of the series now lying between here (Johannesburg) and the Vaal River, "sank in proportion to the height it was tilted at the granite, and consequently all the strata lying between the two great granite intrusions were "tilted towards a common centre, which represents the synclinal axis."

In the years 1901 [1]) and again in the year 1904 [2]) in his memoirs on the geology of the Transvaal MOLENGRAAFF takes the "Old" granite of the Vredefort boss to be intrusive in and younger than the surrounding Witwatersrand Beds, just as in the case of the ,,Old" granite north of Johannesburg at the opposite rim of the curved syncline or trough known as the Witwatersrand basin. He takes the tilting, folding and dislocating of the sedimentary beds at the edges of the basin to be caused chiefly by orogenetic forces, acting mainly in a direction from south to north, contemporaneous with or posterior to the intrusions. He abandons the idea of a system of strike-faults separating in the Vredefort area the groups of sediments one from the other and again from the "Old" granite.

In 1904 [3]) MOLENGRAAFF gives a short outline of the geology of the Vredefort Mountain Land, correlating some of the horizons in the belt of Lower Witwatersrand Beds round the Vredefort Granite with well known horizons in the Witwatersrand. In this paper details are given of the overtilting of the strata in different directions from the central granite boss.

For the first time here the existence is recorded of strong contact-metamorphism in the lowest portion of the sedimentary strata all round the granite-boss, the shaly and slaty rocks up to some distance from the granite being charged with contact-minerals. He comes to the conclusion that the remarkable tectonics of the Vredefort Mountain Land as well as the contact-metamorphism observed in the lowest portion of the sedimentary beds were caused by the intrusion of a huge granite-batholith or boss, the Vredefort boss, which intrusion took place after the deposition of the rocks of the Cape System (now Transvaal System) and before the deposition of the strata of the Karroo System.

He considers the small enclosures of granite found entirely surrounded by rocks of the South African Primary System (now Lower Witwatersrand) to be offshoots of the main intrusive batholith or boss.

STANGER HIGGS [4]) discussing this paper gave a section through the Vredefort area showing the unconformable overlap of the amygdaloidal dolerite (Ventersdorp System) over the Upper Witwatersrand Beds. The author considers the granite to be older than the sediments, but the section gives no intelligible idea of the mutual relations of the different formations.

In the same year HATCH [5]) published a section through the Vredefort

1) G. A. F. MOLENGRAAFF. **59.**
2) ,, ,, **60.**
3) ,, ,, **61.**
4) M. STANGER HIGGS. **38.**
5) F. H. HATCH. **36.**

area from the granite south-east of Venterskroon to the Potchefstroom Townlands, showing the tilting and partial overtilting of the strata of the Witwatersrand, the Ventersdorp and the Transvaal System. He abandons the system of strike-faults shown in his map of 1897 and thus gives a simpler explanation of the tectonics of the Vredefort area in the main points corresponding with that given by MOLENGRAAFF in his paper of 1903.

The same version is adopted by HATCH [1]) in the second much revised edition of his map of the Southern Transvaal published in the years 1903 which is still the best geological map of the entire area in question.

One single paper only gives information on the south-eastern extension of the Vredefort granite-mass and its encircling girdles of sedimentary rocks, where these rocks are partly hidden from view by the overlying beds of Karroo-age. This paper is published by SAWYER [2]) in 1903, where he admits the intrusive character of the granite, saying : "the tilting of the beds "towards the granite mass in places is, I venture to suggest, due to the "shrinkage of the intruded mass whilst consolidating."

In a paper on some granite-masses of the Transvaal, SAWYER [3]) expresses the same opinion on the intrusive character of the Vredefort and other granite-masses, but in a somewhat later paper [4]) he states that "he has "always been of opinion with regard to the granite masses lying east of "Heidelberg and the one lying north of Johannesburg, that they formed "part of the basement-granite, that it had been raised through earth-"movements, affecting the overlying Hospital Hill and Witwatersrand Beds, "which had been thereby thrown into synclines and anticlines." As to the Vredefort granite-mass, although not directly opposing the opinion that this granite might be intrusive, he recalls a statement made by him in 1897 [5]) "that it was distinctly anterior to the Banket formation."

In the year 1904 [6]) MOLENGRAAFF in a short paper stated that he considered the question as to the intrusive or non-intrusive character of the Vredefort Granite open to revision again, in view of the fact, that the non-intrusive character of the granite with regard to the overlying Lower Witwatersrand Beds had now been proved for the bosses north of Johannesburg and east of Heidelberg.

In the same year JORISSEN [7]) described the granite of the Vredefort boss as intrusive into gneiss and crystalline schists associated with it and as non-intrusive in the Witwatersrand Beds.

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1) F. H. HATCH. **35**.
2) A. R. SAWYER. **82**, p. 75.
3) „ „ **81**.
4) „ „ **83**.
5) „ „ **80**, p. 323.
6) G. A. F. MOLENGRAAFF. **62**.
7) E. JORISSEN. **43**.

A year later, in 1905, KYNASTON [1]), discussing JORISSEN's paper, stated that a short visit to the Venterskroon district had left the decided impression that the Vredefort granite was intrusive in the surrounding strata of the Lower Witwatersrand age, and he had particularly noticed the spotted and altered rocks and considered them a typical hornfels due to the contact action of the granite.

In 1906 JORISSEN [2]) referred to the Vredefort area as being due to an arching up caused by centripetal mountainpressure. He denied the existence of contact-metamorphism in the sediments near the contact round the Vredefort boss and considered the granite to be non-intrusive in the Witwatersrand Beds.

In the years 1907 [3]) SANDBERG in a paper on the structural geology of South Africa stated that he regarded the Vredefort granite-mass as a denuded dome formed by omnilateral pressure, the compressing forces having been of equal value in all directions except from south to north.

In 1908 MELLOR [4]) published a paper on the geology of a tract of ground between Eleazar west of Potchefstroom and the Vaal River near Parijs. The paper chiefly deals with the stratigraphy and the complicated structure of the much faulted and compressed Potchefstroom composite syncline, occupied by the Transvaal System. MELLOR also gives a section (Plate VIII) from Parijs to Eleazar and describes in general the topographical features and the geological structure of the Vredefort Mountain Land north of the Vaal River both east and west of this line of section. MELLOR does not express a definite opinion on the intrusive or non-intrusive character of the Vredefort granite. Although not denying the possibility of the granite having been an agent in the early stages of the disturbances of the Witwatersrand System and the overlying rocks, he considers it probable, partly endorsing JORISSEN'S views, that the complete overtilting of the system is due to effects of long continued pressure from outside, combined with the resistance offered by the granite-boss. He states the occurrence of a very persistant intrusion of amygdaloidal diabase at the junction of the granite and the surrounding belt of Witwatersrand rocks. He does not mention the metamorphism of the rocks of the Lower Witwatersrand Beds. MELLOR in this paper is the first to point out the occurrence of elaeolite-syenite in this area. He describes a dyke of this rock, about a hundred feet wide, cutting in an approximately north and south direction the Dolomite and the Ventersdorp amygdaloid on the farms Rietfontein 555, Rietfontein 664 and Buffelshoek. He regards this dyke as the southern continuation of the well-known dyke on Wonderfontein 685 which is connected with the Bushveld Igneous Complex.

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1) H. KYNASTON. **48**.
2) E. JORISSEN. **44**.
3) C. G. S. SANDBERG. **76**.
4) E. T. MELLOR. **53**.

In the same year SANDBERG [1]) in a paper on the age of the "Old" or grey granite of Transvaal pleads strongly in favour of the intrusive character of the granite of Vredefort. He considers its age to be post-Pretoria Series, that is, near to, perhaps even synchronous with, that of the so-called Bushveld or "New" or "Red" granite.

In 1909 BARING HORWOOD and WADE [2]) in a paper on the old granites of Africa came to the conclusion that the old granites of South Africa, although all derived from similar, probably the same, magma, are not all of exactly the same age. Intrusions of this "Old" granite have occurred at various intervals extending over vast geological time. Thus e.g. although admitting that the granite north of Johannesburg is older than the Witwatersrand Beds they endorsed MOLENGRAAFF's idea that the intrusion of the "Old" granite of Vredefort is probably of more recent age than the Pretoria Series (pp. 548 and 549).

In 1914 PENNY [3]) advocated the intrusive character of the Vredefort granite, having observed considerable contact-metamorphism in the lower horizon of the belt of sediments surrounding the granite. He also emphasized the importance in one particular area of complex basic intrusions in the Lower Witwatersrand Beds.

In 1917 SHAND [4]) described the shattered character of the "Old" granite near Parijs, the cracks being filled and injected by an igneous or pseudo-igneous rock which he called pseudo-tachylyte.

The outstanding feature in this brief review of the literature is a considerable divergence of opinion on some of the cardinal geological points.

These points are : the age and with it the character, whether intrusive or non-intrusive in the Witwatersrand Beds, of the granite of the Vredefort boss, and the origin of the peculiar tectonics in the Vredefort area, especially of the tilting and overtilting of the sedimentary formations encircling the granite.

In part this diversity and uncertainty of opinion can be explained by lack of detailed knowledge, but in part it is due to the complexity of the geological problems buried in this area. The evidence obtained by field-work appears indeed to be conflicting and even partly contradictory.

The character of the problem which confronted the authors of this paper when they began their study, can best be gauged by summarizing the facts, which were considered to be well established at that moment :

1. In the Vredefort area there exists an almost circular boss of granite,

1) C. G. S. SANDBERG. **77**.
2) C. BARING HORWOOD and A. WADE. **39**.
3) F. W. PENNY. **66**.
4) S. J. SHAND. **85**.

about 40 km. in diameter, partly hidden from view by overlying Karroo Beds. This granite passes into gneissic rocks in many places and contains belts of schists in which it is intrusive. The granite bears a great resemblance to the so-called "Old" or basement granite of other parts of the Transvaal.

2. All round this granite-boss is a belt of sediments composed of rocks of the Witwatersrand System, the Ventersdorp or Vaal River System, and the Transvaal System, which from the granite up to the lower portion of the upper division of the Transvaal System are highly tilted and overtilted, the strike always coinciding with that of the granite periphery, the dip on account of the overtilting being directed in many places towards the granite, thus leading to an inversion of the succession.

3. The sediments in this belt near the contact with the granite are strongly metamorphosed.

From these facts one is inclined to conclude that the granite is intrusive in the Lower Witwatersrand Beds and that this intrusion can be held responsible both for the contact-metamorphism in the lower strata of the Witwatersrand Beds and for the tilting of the strata all round the boss. The granite, however, being generally accepted as identical with the "Old" granite, and thus older than the Witwatersrand System, cannot be intrusive in it. The problem then is: What is the cause of the contact-metamorphism and what brought about the tilting and the peculiar tectonics of the sedimentary belt all round the granite-boss?

CHAPTER II.

Physical features.

In the Vredefort Mountain Land, as to its physical features, two types of landscapes [1]) can be distinguished. The first type is mainly confined to the central granite-area (see map) and is characterised by the absence of salient topographical features, a dead flat prevailing wherever the granite is covered by overlying horizontal coal-measures. The second type forms a striking contrast with the first, showing a broken and hilly character throughout. This type is confined to the girdle of sediments encircling the granite. In this girdle the strata are without exception highly tilted or vertical, and the more resistant layers are well carved out by denuding agents and now form a succession of narrow, steep and sharp-crested ridges, surrounding the granite-area in a nearly closed circle, like a gigantic amphitheatre. Notwithstanding their moderate height, the extremely rugged and broken character of the ridges gives them an imposing appearance, justifying the name Vredefort Mountain Land, frequently used for the tract of country occupied by these curved hill ranges, of which the centre lies close to the village of Vredefort.

Closer inspection soon reveals that the mountainous and bold character of the country is exclusively found in a stretch of ground, nowhere far distant from the Vaal River. The latter is fairly deeply entrenched and its numerous non-perennial confluents have cut their valleys and gullies to a corresponding depth. It is mainly due to their erosive power that for a distance of some two to four miles all along the river the country shows a great variety of sculpture and notable differences in altitude.

The Vaal River, being here a superimposed river [2]), has as such been

1) Consult on the landscape in the Vredefort Mountain Land also E. T. MELLOR **53**. p.p. 12 and 13.

2) The Vaal River once flowed at a much higher level in horizontal strata of the Karroo System, which then covered the entire Vredefort Mountain Land (fig. 2). In that formation it probably had its bed cut fairly straight in a west-southwesterly direction. Later, when the strata of the Karroo System gradually disappeared by denudation and the underlying formations of the Vredefort Mountain Land were laid bare, the river was forced to cut its bed in the granite and the uptilted strata surrounding it, in which the running water met with great differences in resistance against its erosive power. The Vaal River now has a sinuous course largely adjusted to the complicated geological features of the Vredefort Mountain Land. (See the map at the end of this memoir and the small sketch-map in MOLENGRAAFF's paper **61**).

forced to cut its valley well within the Vredefort Mountain Land. With regard to the entire area the river has an eccentric position and it keeps its bed over a large distance within the north-western portion of the peripheral sedimentary zone, only encroaching upon the central granite-area over a short distance. Consequently in the entire north-western portion of our area the girdle of sediments maintains its rugged and hilly appearance and even the granite-country, where cut by the Vaal River, looses much of its monotony and in places affords even some picturesque scenery. On the Free State side of the river, however, where the girdle of sediments soon gets well away from the river, the quartzite-ridges rapidly diminish in height and finally almost merge into the common plain composed of granite and coal-measures of middle Karroo age. Only disconnected low hills mark the continuation of the girdle, where it embraces the eastern portion of the granite-area.

The Vredefort Mountain Land, considered as a unit, is a still unconquered obstacle in the Vaal River and, within its domain, the river has not yet reached a graded condition, although it is to a high degree adjusted. Both upstream and downstream the erosion is quite mature and the fall of the river insignificant, but within our mountainland erosion is still active and the fall considerable.

The Vaal River enters the hilly country[1]) a short distance downstream of Lindeque at an altitude of 1420 m. and leaves it again 75.6 km. downstream near De Wet's Drift at an altitude of 1300 m., a difference of 120 m., the average fall of the river within the area concerned thus being 1 : 653, which is much, considering that the country all round has been subjected to subaerial denudation for incalculable ages. The contrast with the stretches of the river-bed more upstream is marked. Between Lindeque and Brakfontein somewhat higher up than Vereeniging, a distance

1) We take the hilly country or Mountain Land to begin with the Ventersdorp Amygdaloid. Further from the central granite, in the Transvaal System, the contours of the surface are much smoother.

Fig. 2.

Ideal section showing altitudes in the Vredefort Mountain Land. The Karroo System lies uncomformably upon all other formations. Length of Section 51 km of 67.5 km., the difference in altitude is only 17.7 m., corresponding to an average fall of 1 : 3824.

Thus in contrast with the surrounding country in the Vredefort Mountain Land erosion is still actively at work, witness the numerous rapids in the granite-area and the small waterfalls wherever the river cuts hard rock-ledges at right angles. A fall fully 2 feet high occurs where a layer of exceptionally hard garnet-hornfels forms a kind of barrier across the river, a short distance downstream from Baviaanspoort on the farm Witbank.

The average level of the granite-country south of the Vaal River and also of the plain, where it is composed of rocks of middle Karroo age, is about 1450 m. above sea-level and thus the Vaal River, where it enters the hills has its bed cut only about 35 m. below this plain, whereas at the Wet's Drift, on leaving the hills, it is fully 150 m. lower than this plain. This explains why the landscape in the western or downstream portion of the Mountain Land, comprising the environs of Witbank, Koedoesfontein, Venterskroon, Elandslaagte etc., is more imposing and picturesque than the eastern or upstream portion on Brakfontein, Witkopfontein and other farms.

CHAPTER III.

General geological description.

The sequence of the geological formations, as now adopted by the Geological Survey, and their probable age and correlation with formations in the Cape Province are given in the list on next page.

The Vredefort Mountain Land presents considerable variety with regard to its geological formations. which range from the Swaziland Schists up to the Coal Measures of the Middle Karroo. With the exception of the Rooiberg System and the Waterberg System all systems of rocks met with in the Transvaal are represented.

1. The Vredefort Granite.

The Vredefort granite-boss is nearly circular in shape. Its smaller diameter in a direction from N. to S. measures 38.6 km. ; its larger diameter in a direction from W. to E. measures 39.7 km. The granite-area forms a uniform feebly rolling grasscovered plain, the monotony of which is only interrupted by the occurrence of scattered low hills composed of hummocks of bare granite, partly covered and surrounded by accumulations of rounded blocks, Pl. I fig. 1 and 2, features which are familiar in granite-landscapes all over the world. Near the Vaal River which cuts across a small portion of the granite-area and in a lesser degree in and next to the valleys of spruits, which are tributaries of the Vaal River, these hillocks are more numerous and dotted together, and in places, as e.g. in the lower portion of the farm Koppieskraal, give rise to some picturesque scenery.

The average altitude of the granite-plain south of the Vaal River is between 1433 and 1464 m., that of the much smaller portion of the granite area north of the river about 1403 m. The farm Witkopjes No. 107, one of the highest points of the granite-area (1485m.), commands a fine and highly characteristic view. The entire granite-area is seen to be surrounded by several encircling ranges of hills, following one after the other as so many wings on a stage. Towards the east and south-east these ranges dwindle down and, with the exception of a few isolated hills, disappear together with the granite below the cover of horizontal strata of the coal measures. The hills next to the granite are sharp-crested and all show well-

TABLE OF GEOLOGICAL FORMATIONS OF THE TRANSVAAL.

Main Igneous Intrusions.	Sedimentary Formations Transvaal.	Probable Equivalent Cape.	Age.
	Karroo System		
	Bushveld Amygdaloid	Volcanic Group	
	Bushveld Sandstone Series	Cave Sandstone Red Beds.	Triassic
	Beaufort Series	Beaufort Series	Permian
	Coal Measure Series (Ecca)	Ecca Series	
	Glacial Conglomerate and Shales	Dwyka Series	Carboniferous
	⁀‿⁀‿⁀‿⁀‿		
	Waterberg System		
	Waterberg Series	Matsap Series	Pre-Devonian
	⁀‿⁀‿⁀‿⁀‿		
Bushveld Igneous Complex, intruded into the Rooiberg System; pre-Waterberg age.	Rooiberg System		
	?		
	Transvaal System		
	Pretoria Series	Griqua Town Series	Pre-Devonian
	Dolomite Series Black Reef Series	Campbell Rand Series	
	⁀‿⁀‿⁀‿⁀‿		
	Ventersdorp System		
	Klipriversberg Amygdaloid Groups of Sediments	Ventersdorp System	?
	⁀‿⁀‿⁀‿⁀‿		
Old or Grey Granite, including the Vredefort Granite. The intrusion of this granite took place after the deposition of the rocks of the Swaziland System and prior to the deposition of the rocks of the Witwatersrand System.	Witwatersrand System		
	Upper Lower		?
	⁀‿⁀‿⁀‿⁀‿		
	Swaziland System		
	Moodies Series		?
	Crystalline Schists		
	⁀‿ = "unconformity"		

developed often imposing dip-slopes facing the central granite. Those nearest to the granite are composed of quartzites of the Lower Witwatersrand, those further away of quartzites, sandstones and conglomerates of the Upper Witwatersrand. Behind those rows of hills another semi-circular range appears, composed of effusive rocks belonging to the Ventersdorp System, which by the smooth and dome-shaped outlines of its composing hills forms a marked contrast with the rugged and conspicuously chiselled contours of the hills in the foreground.

The Vaal River has cut a broad and shallow valley in the granite-area. The spot where the Vaal River enters the granite-area is 1415 m. high, and the spot where it leaves it again 1340 m. Thus the river in its course through the granite-area increases the depth of its bed compared with the mean level of the granite-plateau from 35 to 110 m. Although the banks of the river in the granite-area are steep in places, a gorge-like riverbed is nowhere formed.

The granite of the Vredefort boss which in this area represents the Old or Grey granite mentioned in the table of the geological formations (see p. 14) varies in texture and appearance. Its most widespread variety is a coarse to medium-grained rock of decidedly porphyritic appearance. The most conspicuous mineral, the orthoclase, occurs in crystals often twinned after the Carlsbad-law, attaining a diameter ranging from 5 to 20 mm. and dominating in size all other constituents, so as to give the rock its porphyritic appearance. The rest of the rock is composed of a fairly even-grained crystalline mixture of plagioclase and quartz. The former mineral is grey to whitish and more transparent than the orthoclase; it is an acid plagioclase (oligoclase) as is shown by its relatively low refractive index being on the average lower than that of quartz, and by its low extinction. The twinning planes after the albite-law, though always present, are often very faint. Plagioclase predominates over orthoclase in more than one locality. Microcline which is a predominating mineral in the "Old" granite of several localities in the Southern Transvaal is, in the Vredefort boss, only reported from the farms Witkopjes and Zijferfontein. A peculiar micropegmatitic intergrowth of plagioclase and quartz showing characteristics of myrmekite, is often found growing out from plagioclase crystals, apparently as an end-product of crystallisation. Femic constituents are not abundant and are represented by biotite ranging in colour from brown to bright green and often more or less altered into chlorite. The flakes of the biotite are more or less clustered together in patches. Muscovite occurs locally together with biotite.

Amongst the minor constituents such as magnetite, apatite, zircon [1]) the latter may be mentioned, because pleochroic halos are very well developed

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1) A variety rich in prisms of zircon of microscopic dimensions was collected by one of the authors in the year 1890 near the village of Vredefort. **58**, p. 189.

around its crystals where enclosed in biotite and better still where such biotite is converted into chlorite.

The chemical composition of a fresh sample of this granite from near the bridge over the Vaal River at Parijs is as follows :

	%
SiO_2	71.0
TiO_2	0.35
ZrO_2	Nihil
Al_2O_3	15.5
Fe_2O_3	1.5
FeO	1.5
MnO	Nihil
CaO	1.6
MgO	0.7
Na_2O	3.8
K_2O	3.3
P_2O_5	0.2
CO_2	Nihil
Loss at 110°	0.4
Loss on ignition	0.8
Sp. Gr. 2.7	100.65

Analysis by H. G. Weall, Government Laboratories, Johannesburg.

The granite throughout the Vredefort boss has a somewhat gneissic appearance caused by more or less marked parallel arrangement of its constituents. Rarely only do the phenocrysts of orthoclase fail to show this tendency to parallelism.

Frequently the granite is streaky, resembling a granite-gneiss, e.g. at Parys, and in places it passes into banded orthogneiss.

SHAND in describing the streaky granite-gneiss at the township of Parijs separates the red portion rich in orthoclase from the grey portion rich in oligoclase. He says [1]):

,,The granite in the neigbourhood of Parys is a streaky granitic gneiss, composed of red and grey elements. Sometimes the red forms patches and streaks within the grey, elsewhere the grey matter is similarly enveloped by the red, or again the two elements may constitute alternate bands. The red matter often forms veins and bands of coarse pegmatite which run parallel to the direction of foliation of the grey rock, but in other cases such veins cut sharply across the foliation. These pegmatites are occasionally very

1) S. J. SHAND, **85**, p. 199.

coarse-grained graphic granites. When extensive exposures are studied, it becomes evident that the red portion is of later consolidation than the rest of the rock. Isolated "floaters" of banded grey paragneiss can be found embedded in the red granite; and, to my mind (although I have not made a special study of the gneiss-granite), the matter is susceptible of one interpretation only, as follows: — the grey facies of the granitic gneiss results from impregnation, metamorphism, and eventual assimilation of sedimentary country-rock by the ascending magma, while the red is the residual portion of the same magma. Probably neither part reproduces the initial composition of the magma exactly."

Certainly these relations do not hold good throughout the area in question, but we have found phenomena suggesting the same explanation in several other localities. Amongst these may be mentioned Kafferkop about 2 miles south-west of Parijs on the road to Vredefort, where the granite is full of streaks of such schistose rocks as paragneiss, biotite-schist and amphibolite, the latter containing lenses of quartzitic material, probably undigested portions of sediments taken up by the intruding granite.

The rocks in which the granite was intruded belong most probably to the Swaziland System, dealt with in the next section.

Pegmatite veins are frequent throughout the granite-area; they consist of pale to bright red orthoclase and quartz in different modes of intergrowth, and of mica. In places this is present as biotite, but more often as muscovite. The coarse-grained varieties afford fine examples of graphic granite as e.g. near Vredefort and at Witkopjes.

Although the pegmatite veins are much more numerous in one place than in another, they are frequent enough to indicate that the granite must have been rich in juices and must have given rise to strong pneumatolytic phenomena during consolidation.

We fail to find any regularity in the occurrence of the pegmatites, but the fact is noteworthy that there appears to be no difference in their frequency in the marginal portion of the granite, compared with the central portion. Two systems of pegmatite veins intersecting each other are sometimes met with and one system may be faulted over a small distance against the other.

The Vredefort Granite has been subjected to considerable pressure, as shown under the microscope by cataclastic structure. Not seldom the crystals of quartz and felspar show many cracks filled with a mosaic of crushed material. Nowhere, however, has the pressure given rise to a distinct schistosity. We do not believe that the streaky and more or less schistose structure which, as mentioned above, is frequent in the Vredefort boss, is caused by pressure. The streaks do not show a prevailing direction. Although alignments from W.-E. to N.W.-S.E. appear to be somewhat favoured in the localities visited, yet the streaks in the granite are usually sinuous without showing a constant direction. It appears to us that the cause of the gneissic appearance must be sought in movements prior to consolidation, and that of its mineral variation in assimilation of invaded country-rock.

The irregular composition of the granite may perhaps have been caused by injection of juices of a later magma during the period of its uptrusion in connection with the updoming of the area. In this case the Vredefort granite ought to be considered as a migmatic rock.

At many places in the granite-area one meets with highly irregular usually dark-coloured narrow veins of a rock, which SHAND described as pseudo-tachylyte. This rock is genetically connected with the phenomena of pressure and crush (see Chapter III, 8).

It appears to us that a detailed study of the Vredefort granite and its pegmatite veins, which lies outside the scope of this paper, may lead to interesting results.

Round the periphery of the granite-area a series of occurrences of basic rocks of gabbroid character is found in the form of dykes and sills, but including one dyke with acid affinities on the farm Supra ; these basic rocks are discussed in the section dealing with the marginal intrusions.

2. THE SWAZILAND SYSTEM.

In the Vredefort granite-boss some belts of schists of limited extent occur. The largest of these belts is found in the eastern portion of the granite-area west and south-west of the station Greenlands (formerly Vredefort Road Station) of the Pretoria—Bloemfontein Railway line (see Map).

SAWYER [1]), in 1903, mentions these schists on the farm Blauwboschpoort, and on his map indicates the rocks as actinolite-schists and talc-schists. The strike is given by him to be about E.-W. to E. 20 N.-W. 20 S., and the position vertical. In the index to the map SAWYER shows these schists as part of the Hospital Hill Series (Lower Witwatersrand) but admits that their planes of division are at right angles to the bedding planes of the Hospital Hill Quartzites. In the year 1922 one of the authors could corroborate SAWYER's statements on the farms Zwartkoppies and Blauwboschpoort, in general. We take these schists, however, to be unconformable to the Lower Witwatersrand Beds (Hospital Hill Beds) and to belong to an older group of rocks.

Among the amphibolites a variety preponderates in which the actinolite is colourless and does not show any pleochroism, and is therefore not distinguishable from tremolite. The prisms of actinolite are fairly parallel to one another and are quite fresh; they are imbedded in a uniform and apparently quite isotropic kind of groundmass. A very feeble almost imperceptable double refraction can, however, be detected in places ; it is not easy to be certain about this, because minute prisms of actinolite are included in this pseudo-isotropic mass and hamper the observation.

This pseudo-isotropic groundmass has a faint greenish tint and as to its

1) SAWYER, **82**, pp. 75—76

mean refractive index (1.585) and its density (both determined in powder) corresponds to chlorite.

We, therefore, take the mineral composing this mass, interstitial between the actinolite crystals, to be chlorite, with an unusual low double refraction. No other minerals besides a few specks of ore occur in this type of schists.

In some of the varieties the prisms of actinolite are stout, large and thickly crowded, little room being left for the groundmass; in others they are slender, often like needles, and the pseudo-isotropic groundmass is strongly developed.

The strike of the schists is on the average W 4 N and the dip nearly vertical. Besides amphibolites and talc-schists also some biotite-schists occur. They are cut by veins of rather coarse aplite, in places much like pegmatite, and both the schists and the aplite-veins are again cut by veins of pseudo-tachylyte.

Quartz-veins are abundant and, like the schists themselves, in places mineralised carrying malachite and copper-pyrites.

Several shafts are sunk and cuttings made in these schists for prospecting purposes, most of them in the last decade of the past century. It is thanks to them that this formation can even now be well studied. Natural outcrops are poor and the schist-belt, the boundaries of which are not well known, is largely covered by surface-soil or by outliers of sandstones, shales and dolerites belonging to the Karroo System. The schist-belt, where visible, is surrounded by the Vredefort Granite.

A little south-west at the boundary between the farms Enkeleboom and Broodkop a narrow belt of gneiss is exposed in a small kopje as a somewhat porphyritic biotite-gneiss poor in femic constituents. The strike of the gneiss is somewhat variable. JORISSEN [1]) who first described this locality gives the strike of this gneiss N 58 W magnetic, i.e. plus or minus N 82 W true bearing. At the eastern slope of the kopje both the granite and the gneiss are cut by a network of veins of pseudo-tachylyte.

Adjoining the gneiss quite near the fence between the farms Broodkop and Enkeleboom amphibolite is exposed in a shaft; this is an actinolite-schist showing a granular mixture of quartz and plagioclase developed between the prisms of the amphibole. The pleochroism of the actinolite is as usual, 𝔞 pale yellowish green, 𝔟 dirty olive-green, 𝔠 bluish green. Biotite in dirty brown flakes is present. The planes of division of this amphibolite stand vertical and it is cut by veins of pegmatite. From this spot the belt of amphibolites etc. can be traced through the farm Blauwboschpoort almost as far as Vredefort Road Station.

A much narrower belt of schists occurs on the farm Witkopjes about 16 km. south-south-east of the Vredefort village. About 365 m. east of the road between two low granite-hummocks this belt is exposed in a long prospecting trench dug in or before the year 1890. It has a thickness of

1) E. JORISSEN. **43**. p. 156.

about 180 m. The strike of the schists is N 70 W and the dip very steep to the south, approaching 90°. Fine-grained dark-green actinolite-schists alternate with soft more talcose varieties. Some of the latter show blades of talc up to an inch long; the actinolite is sometimes green with the usual fairly strong pleochroism, but more often is it colourless and non-pleochroic. The actinolite-schists [1]) containing the latter variety of amphibole belong to the same type as described above from Blauwboschpoort, a peculiar apparently homogeneous and isotropic interstitial mass of chlorite lying between colourless actinolite-prisms. The schists are cut by many veins of quartz-feldspar pegmatite and finer aplite, closely resembling those found in the schists on Blauwboschpoort.

We are of opinion that these belts of schists on Blauwboschpoort and Witkoppies belong to the Swaziland System, because similar belts with prevailing east and west strikes are met with in the granite-boss north of Johannesburg and again in the Low Country east of the Transvaal Drakenberg escarpment; from the Barberton District they are described in detail by HALL [2]). At these localities the belts of schists are cut by veins of pegmatite and aplite in a similar way as in the Vredefort area. It is obvious that the schists are older than the Vredefort granite-boss and they probably represent the remnants of an older formation, most likely belonging to the Swaziland System which was invaded and largely replaced by the granite.

Another small belt of schists — of quite a different character — came to our notice from the eastern portion of the farm Kopjeskraal adjoining Rietpoort north of Parijs. Here a vertical belt of amphibolite in the granite is exposed in a shaft, but no outcrops were observed and the thickness of the belt is unknown. Its dip is 90° or nearly so. Macroscopically the rock is well schistose and dark green; under the microscope it consists mainly of stout prisms of strongly pleochroic actinolite, 𝔞 pale yellowish green, 𝔟 dirty brownish green, 𝔠 bluish green, with a granular mixture of quartz and plagioclase connecting the prisms. Zoisite in small plump prisms is abundant. All the minerals except the quartz, which fills all the openings, show a well marked sieve-structure. This amphibolite is quite different in character from those observed in the belts in the eastern and southern parts of the Vredefort granite-boss, and is most likely an igneous rock which has been thoroughly changed and recrystallised by dynamic and thermal metamorphism.

3. THE WITWATERSRAND SYSTEM.
(Map and Pl. IV, fig. 1 and 2.)

The Vredefort granite-boss is encircled by a belt of sedimentary rocks.

1) The occurrence and microscopical appearance of these schists were first described by MOLENGRAAFF, but this description contains some errors which are corrected here. Compare G. A. F. MOLENGRAAFF, **58**, pp. 193—194.

2) A. L. HALL, **29**.

the lower portion of which represents the Witwatersrand System. Although the belt of sediments around the granite is not uninterruptedly visible, and towards the east and south over considerable distances is hidden from view by overlying horizontal strata of the Coal Measures, there can be no reasonable doubt that below those rocks of the Karroo System the belt of Witwatersrand rocks would be found, and thus at a certain depth forms a continuous girdle all round the granite-boss. The largest gap in this girdle occurs between Witkopjes and the southern boundary of Prospect over a distance of 45 km. measured along the inferred periphery of the granite. The country within this gap, although known to be made largely of strata of the Karroo is, however, geologically unsurveyed as yet, and outcrops of Lower Witwatersrand Beds may exist there, which have not come to the notice of the authors. A smaller gap occurs towards the east between the southern end of Wittepoort and the southern portion of Marseilles, which is about 11 km. wide. The total width of the gaps amounts to about one third of the entire circumference of the Vredefort granite-boss.

The granite is accepted by the authors to be non-intrusive in and older than the sediments of the Witwatersrand System for the following reasons: The contact between the granite and the adjoining beds of the Witwatersrand System shows nowhere signs of being eruptive. Although the many pegmatite-veins within the granite prove that this rock must have been rich in juices, not a single apophysis of the granite nor a vein of pegmatite has been found passing from the granite into the adjacent sediments. Where the contact could be studied — as a rule it is covered by surface-soil — it always gives the impression as if the sediments of the Witwatersrand have been deposited on a much older granite-soil. Besides, the schistose character of the granite and the total independence of its schistosity as well as that of the invaded older schists (Swaziland System) prove that the granite has a long history of its own before the Witwatersrand System was deposited.

It must be admitted that apparently several phenomena appear to plead the other way. The rocks all round the granite — although in different degrees — show thermal metamorphism and are intensely altered, in places up to distances of 5.5 km. from the edge of the granite, the metamorphism appearing to decrease with increasing distance from the granite. Again the granite is not in all places in contact with the lowermost strata of the Witwatersrand System. One or more of these then are totally wanting and the granite is found in direct contact with strongly metamorphosed higher members of the complex (as e.g. on Zijferfontein and Tweefontein), giving the impression as if the granite had invaded the sediments and had assimilated the lower portion of the sedimentary belt.

The authors give more weight to the facts which plead in favour of the non-intrusive character and older age of the granite with regard to the encircling sediments than to those which appear to be adverse to this conclusion; the probable explanation of this apparent contradiction will be given below in Chapters V and VI.

The writers are of opinion that the granite of the Vredefort boss is older than the rocks of the Witwatersrand System, a relationship also accepted for the granite of the Heidelberg boss and that north of Johannesburg. They admit, however, that the Vredefort Granite has certain characters of its own, distinguishing it from other granites in the Southern Transvaal, e.g. the prevalence of red orthoclase giving the granite in many places a bright red colour, also the frequent development of a streaky texture and the scarcity of microcline, which mineral is rather common in the granite of the other bosses.

The belt of sediments in immediate contact with the granite represents the lower division of the Witwatersrand System. This system has been studied in considerable detail on the Witwatersrand by MELLOR [1]) and in the Heidelberg District by ROGERS [2]) and it can be safely upheld, that the Lower Witwatersrand System belongs to those groups of rocks in the Transvaal, the stratigraphy of which is now best known. Hence it has been feasible to recognise in the sediments around the Vredefort Granite the same horizons in the same order as have been described from the environs of Johannesburg and Heidelberg. This is important, because it is therefore proved beyond doubt, that the rocks next to the Vredefort Granite really represent the lower division of the Witwatersrand System in normal sequence, confirming so far previous statements, and this notwithstanding the fact, that in the Vredefort area these rocks are higly metamorphosed, whereas near Johannesburg and Heidelberg the identical strata show no such metamorphism.

From the granite upwards (the strata being almost everywhere overtilted and consequently dipping towards the granite, the word ,,upwards" here means ,,stratigraphically upwards") the following groups of strata can be distinguished in the Witwatersrand System. The names here given to the successive groups are those now generally accepted for the subdivisions of the System in the Witwatersrand and near Heidelberg.

a. *The Sericite Schists.*

These schists, where exposed, form a narrow belt between the granite and the overlying (in reality at the outcrop underlying by overtilting) lowermost bar of the Orange Grove Quartzites, but they were also observed between the latter and the Basal Amygdaloid. They have originated from quartzites as a result of the intense pressure during updoming [3]). On Zijferfontein near the boundary of Vergenoeg these sericite-schists which are overtilted with the entire belt of sediments strike N. 46 W. parallel to the periphery

1) E. T. MELLOR. 54.

2) A. W. ROGERS. 71.

3) The same cause probably accounts for the occasional occurrences of analogous schists along the boundary between the granite and the Basal Amygdaloid.

of the granite-boss and dip 70° south-west towards the granite. Their position is quite conformable to the stratigraphically overlying quartzites. They are well exposed in a cutting running from the quartzite well into the granite right across the belt of schists which is 5 m. thick. JORISSEN [1]) first mentioned the sericite-schists of this locality in the year 1905, but PENNY [2]), in 1914, did not find them.

On Witbank due west of the gabbro-kopje a good outcrop of these schists exists ; here they are again intercalated between the granite and the lowermost quartzite of the Orange Grove Quartzites and are perfectly conformable with the latter. On Rietpoort not far from the boundary with Kopjeskraal sericite-schists have been observed between the Orange Grove Quartzite and the underlying Basal Amygdaloid. In all these localities the schists are grey to white, in places stained reddish, and possess the usual strong silky lustre characteristic of sericite-schists. Sections under the microscope show the features common to sericite-schists. The schist found on Zijferfontein is richer in quartz-grains, strewn in the dense mat of interwoven sericites-flakes, than that on Witbank and might be called a schistose grit with a very strongly developed sericite-felt between the quartz-grains.

From our observations it appears that these sericite-schists are confined to a few localities, but it is quite possible that they are much more widespread, because the chances of finding outcrops of this soft rock are meagre. Had it not been for the cutting, the occurrence of the belt of sericite-schists on Zijferfontein would have remained unknown because surface-soil completely hides their outcrop.

Similar sericite-schists are recorded from the Witwatersrand by KYNASTON [3]) in the same stratigraphical horizon, i.e. at the base of the Lower Witwatersrand Beds between the Orange Grove Quartzite and the underlying granite in the escarpment below the Sans Souci Hotel.

b. *The Basal Amygdaloid.*
(Map and Pl. XXXVI—XXXVIII.)

Over a great portion of the periphery of the granite-boss the lowermost member of the group of Lower Witwatersrand Beds is a body of a peculiar fine-grained amphibolite which, where it occurs, is always found between the granite and the lowermost quartzite-body of the Orange Grove Quartzites. This rock is highly metamorphosed and will be described more fully

1) E. JORISSEN. **43**, p. 156.

2) F. W. PENNY, **66**, p. 330. PENNY, who in 1913 did a great deal of detailed geological surveying on Vergenoeg and the adjoining farms, states that at that time no cutting existed exposing the contact between the Orange Grove Quartzites and the underlying granite. In 1922 we had no difficulty in finding the cutting described by JORISSEN, which in fact shows the contact excellently. Perhaps this may be explained by the fact, that the actual cutting is not on the farm Vergenoeg, as stated by JORISSEN, but on the adjoining farm Zijferfontein, quite near the boundary with Vergenoeg.

3) H. KYNASTON, **49**, p. 59.

in the second division of Chapter IV of this memoir dealing with the metamorphism of the igneous rocks; prior to its alteration it most probably was a basic lava.

The belt of amphibolite — originally the flow of basic lava — stretches from Vlakspruit (it may be found still further south, but that portion of the granite periphery was not visited by the authors) over Rietkuil, Witbank, Kopjeskraal and Rietpoort to Brakfontein ending on that farm a short distance north-west of the Vaal River (see Map); on this stretch it appears to be interrupted now and then, specially in the disturbed country just south of the Vaal River on Witbank; this apparent lack of continuity is, however, clearly due to displacements through faulting. It reappears only in patches on the Free State side of the Vaal River east of Brakfontein. The width is about 600 m. on Rietpoort and the eastern portion of Kopjeskraal, taking the dip to average there 60° towards the granite. In other places it is thinner as shown on Pl. XXXVIII.

In the field the amphibolite has a fairly uniform appearance resembling a diabase. At the surface it forms large boulders or presents rounded fairly smooth surfaces with a reddish brown crust, which is not rugged. The fresh rock underneath this crust is dark greenish and with a strong pocket-lens many small needles of amphibole are seen in it. In many places the rock is amygdaloidal (Pl. II, fig. 2); oval or somewhat irregular and often elongated white patches protrude from the sombre skin of the rock. The stretching of the amygdales in one direction parallel to the floor of the rock (the surface of the granite) shows in places fairly well the flow-structure of the original lava. Since the rock has a pronounced granulitic microstructure, the term „amygdaloidal hornblende-granulite" would be appropiate.

The chemical composition is as follows:

SiO_2	55.7 %
TiO_2	1.15
Al_2O_3	14.35
Fe_2O_3	.65
FeO	8.65
MnO	.20
CaO	8.95
MgO	7.30
Na_2O	2.2
K_2O	trace
P_2O_5	.20
H_2O (110° C.)	.2
Ignition loss	.75
Total	100.3

Sp. Gr. 2.95

Basal Amygdaloid from Rietpoort, North of Parys. Analysis by H. G. WEALL, Government Laboratories, Johannesburg.

The material for this analysis was selected to be as free from amygdules as possible, but it was impossible to avoid minute fragments of quartz derived from very small quartz-amygdules getting into the material ; for this reason the silica percentage is probably slightly too high.

The figures clearly point to an original diabase-magma.

At three localities, on Rietkuil, Rietpoort (see fig. 9 and Pl. XXXVI) and Brakfontein we found large blocks of highly metamorphosed sediments included in this amphibolite. These gave rise to great difficulties in finding an explanation of their mode of occurrence. On Rietkuil and Brakfontein they consist of amphibole-cordierite-hornfels, at Rietpoort of actinolite-garnet-cordierite-hornfels. At first it was thought that the amphibolite was an altered intrusive sill, and that the amygdales represented, not the filled gaspores of a lava, but recrystallised small xenoliths. In that case the blocks would represent large xenoliths of highly altered sediments taken up in the sill and carried to their present places during its intrusion. The strongly marked amygdaloidal character which the amphibolite displays at several localities, the position of the blocks more or less along the same horizon and with their longer axes parallel to the strike of the overlying sediments, and the insufficient support given by field-evidence to the intrusive character of the supposed sill decided us to abandon that view. It now appears to us that the amphibolite was formed by several more or less amygdaloidal lava-flows, between which at least one argillaceous band of sediments was intercalated and that later, by intense metamorphism, these rocks were welded together and the lines of demarcation between the different flows destroyed. We admit that this conception does not give a satisfactory explanation of the fact that now only a few blocks wide apart one from another represent a once more or less continuous sedimentary deposit.

The rock was described by MOLENGRAAFF [1]) in 1894 as amphibolite and has been mentioned by PENNING as a dolerite, by DRAPER as igneous, by BUNKELL as basaltic, by HATCH again as igneous.

All these observers agree in taking the rock as being, around the Vredefort granite-boss, intercalated between it and the Lower Witwatersrand sediments, thus indicating its position in a general way.

1) G. A. F. MOLENGRAAFF, **58**, p. 194, describes a non-amygdaloidal type of this rock, found by him on Vlakspruit as follows: Der feinkörnige Aktinolithschiefer, welcher am Rande des Granitmassivs am Wege von Vredefort nach Reitzburg ansteht, besteht aus schilfigem Aktinolith, dessen Säulen im Mittel 0,32 mm lang und 0,05 mm breit sind. Dieses Gestein ist dem Aktinolithschiefer der Witkopjes sehr ähnlich, unterscheidet sich jedoch durch einen bedeutenden Gehalt von gerundeten Quartzkörnern nebst spärlichem Auftreten von Plagioklas-krystallen und Zirkonsäulchen.

c. *The Orange Grove Quartzites.*
(Map and Pl. IV, fig. 1 and 2.)

The Orange Grove Quartzites consist of five bars with intercalated strata of more or less ferruginous shales, and in most places also a sill of epidiorite. Some of the bars of quartzite may, however, unite and then the entire succession may be simpler. The epidiorite is usually intruded between the third and fourth quartzite-bars ; in some places as on the western portion of Rietpoort (Pl. IV, fig. 2) the sill is 355 m. thick, but elsewhere it may dwindle down to a few feet, or may be wanting. These variations give the complex of the Orange Grove Quartzites different aspects in the field. On Witbank (Pl. IV, fig. 1) the succession is complete, but none of the components attains a great thickness there. The dip is on the average 60° towards the granite. On Rietpoort (see Fig. 9 and the section Pl. IV, fig. 2 taken west of the road from Parijs to Potchefstroom) bars 4 and 5 of the quartzites are united and together form a powerful high ridge, the crest of which commands a fine view over the greater portion of the Vredefort granite-area. The sill of epidiorite intruded between the bars 3 and 4 is 355 m. thick, and the southern slope of the ridge mentioned above as well as the valley between it and the much lower but conspicuous little ridges composed of the lower bars of quartzite are covered by large weathered out boulders of this rock. More to the east between Oud Rietpoort (Mr. Prinsloo) and Klein Rietpoort (Mr. Grobbelaar) the sill in the Orange Grove Quartzites is wanting and all the bars of quartzite are united and form together one flat-crested broad ridge, the southern slope of which is occupied by Basal Amygdaloid and the northern slope by hornfels. They are strongly overtilted here (Pl. V, fig. 2). Still further east near and on Brakfontein the Orange Grove Quartzites are more surbordinate and their outcrops are little marked in the landscape.

More east again, on the Free State side of the Vaal River on Anna's Rust and the adjoining farms, the Orange Grove Quartzites are little developed. Further, on Tweefontein 385, Zijferfontein and Vergenoeg, PENNY [1]) distinguished in the Orange Grove Quartzites two bars of quartzite separated by a belt of ferruginous slate. Near the boundary between Tweefontein and Zijferfontein and again in the southern portion of Vergenoeg the Orange Grove Quartzites stand out as distinct narrow ridges but in other places e.g. on a large portion of Zijferfontein they are absent by faulting and the granite is found in direct contact with the belt of ferruginous shales or slates belonging to a higher stratigraphical horizon, viz. just on top of the Orange Grove Quartzites. These relations are well illustrated on PENNY's map (Fig. 8).

South-east of Vergenoeg on Klipfontein 70 the Orange Grove Quartzites, being represented by one body, adjoin the granite and dip towards it with

1) F. W. PENNY, **66**.

an angle of 70—80° or even more. On Zwartbult the Orange Grove Quartzites dip 85°—70° away from the granite, and further south-east on Nugget they are somewhat faulted and dip 40—80° away from the granite. A small distance from there towards the south-east on the farm Wittepoort the Orange Grove Quartzites, which are well exposed near the dam, dip 83° and in a higher horizon about 60° away from the granite. In the southern portion of the same farm they are either vertical, or overtilted so as to dip towards the granite.

On the southern portion of Wittepoort according to SAWYER[1]) the Quartzites crop out again dipping 45° towards the granite. Further south they are covered by dolerite and sandstones of the Karroo for about 7 miles and reappear dipping away from the granite on the extreme eastern corner of Zwartkoppies and along a small hill at the northern apex of Sahara near Greenlands Station. On Prospect and along the boundary between Blauwboschpoort and Allendale they are well exposed in a hill trending west of the railway parallel to it. The quartzites consist of four bars, with intercalated strata of partly ferruginous altered shales, dipping 55—80° west-north-west, towards the granite. Thus the strike of the Orange Grove Quartzites is here about at right angles to that of the schists, which crop out at a small distance towards the west. Taking into account that the quartzites are overtilted, they clearly overlie the schists unconformably.

Summarizing: The Orange Grove Quartzites and associated shales form a continuous girdle all round the Vredefort granite-boss which towards the south and east, however, is largely covered by much younger horizontal strata of the Karroo (Coal Measures). The strike is, with a few local exceptions, parallel to the periphery of the granite. The dip is as a rule high, rarely away from the granite, but much oftener, by overtilting towards the granite. The position of the strata is entirely independent of that of the schists which form belts within the body of the granite. Over a considerable distance, specially towards the north in the Transvaal, a huge sill of epidiorite is intruded between the quartzites of the complex.

d. *The Water Tower Slates.*
(Map and Pl. IV, fig. 1 and 2.)

On top (stratigraphically) of the Orange Grove Quartzites a thick body of strata of hornfels follows which are overtilted and metamorphosed, and prior to their metamorphism must have been more or less ferruginous and partly somewhat silliceous shales and slates comparable to the Water Tower Slates of the Witwatersrand. The lowermost portion of this body is generally highly ferruginous and these beds are often more or less contorted, so as to resemble the typical "Contorted Beds" which belong to a higher

1) A. R. SAWYER, **82**, p. 76 and plan.

horizon. These beds consist of actinolite-(amosite) hornfels and actinolite-garnet-hornfels crowded with small crystals of magnetite. In this lower portion a thin bed of felspathic quartzite occurs, which at the Witwatersrand is known as the „speckled bed", a name given to it by DRAPER. The persistence and the constancy in composition of this tiny band over large distances is very remarkable. On top of these somewhat less ferruginous beds follow, in which are intercalated non-ferruginous rocks, originally clay-shales or slates now altered into cordierite-biotite-hornfels and andalusite-cordierite-biotite-hornfels, generally well stratified. Higher in the complex the strata are more ferruginous again and contain an intruded sill of diabase, altered into epidiorite. Somewhat higher again these ferruginous rocks are as a rule much contorted and most probably represent the well known contorted bed of ferruginous Hospital Hill Slates, a useful marker in tracing the detailed succession of the Lower Witwatersrand System.

e. *The Hospital Hill or Green Quartzites.*
Map and Pl. IV, fig. 1 and 2.

Some distance higher the hornfelses are more siliceous and garnetiferous, and are soon followed by the first strong bar of quartzites belonging to the complex of strata known on the Witwatersrand as the Hospital Hill or Green Quartzites. These are the Lower Green Quartzites. On top of these quartzites occurs a very persistent narrow belt of an exceedingly coarse actinolite-rock with a very striking appearance in handspecimens. On top of these follow cordierite- and andalusite-hornfels alternating with ferruginous beds and these again underlie (overlie by overtilting) a powerful complex of quartzite, the main body of the Green Quartzites, in which are intercalated some layers of hornfels. In Baviaanskrans on Witbank an extremely hard layer of an andalusite-cordierite-biotite-hornfels offers more resistance to weathering and erosion than the adjoining quartzite and thus stands out and locally forms the highest points of the crest of that ridge. The Upper Green Quartzites in the Vredefort-area as a rule form a strong and well marked ridge and where near the Vaal River the erosion has sculptured the landscape fairly deeply, this ridge shows a magnificent dipslope (Pl. III, fig. 2) towards the granite. The hornfels which overlies (stratigraphically underlies) this quartzite in many places forms a broad shoulder against it, and the narrow belt composed of Lower Green Quartzite is just visible as a slight protrusion on its slope.

On top of the main bar of the Upper Green Quartzites follows a succession of thinner bars of quartzite alternating with hornfels, amongst which is a ferruginous hornfels and a type with densily crowded pink garnets as conspicuous constituents. The latter is a very hard rock and, where it crosses the Vaal River, determines a distinct little waterfall. These strata do not form persistent layers over great distances. More persistent are gritty schistose sericite-rocks, which are beautifully plicated, and appear to occur regularly on top of the Green Quartzites. On Witbank and Kopjeskraal these schists are separated from the main body of Green Quartzites by the types of hornfels just mentioned, but on Deelfontein they follow immediately on top of the Green Quartzites. The Hospital Hill or Green Quartzites are overtilted in the same way as the Orange Grove Quartzites and their dip often shows considerable variations. Thus in the main portion of the Baviaanskrans on Witbank (Pl. III, fig. 2) the strata dip 60° towards the granite whereas in the Baviaanspoort where the Vaal River cuts across the ridge they stand nearly vertical (Pl. III, fig. 1).

f. *The uppermost portion of the Lower Witwatersrand Beds and the Upper Witwatersrand Beds.*

The discussion of the sedimentary column above the Upper Green Quartzite lies outside the object of this paper and we examined portions of these higher horizons only where igneous rocks occur, probably connected with the genesis of the Vredefort dome, or again at some places with the object of fixing the upper limit of the metamorphism.

Below Witbank in a direction away from the granite beyond the big ridge of Green Quartzite follow three well marked ridges of quartzite separated from the former and from one another by parallel valleys due to the presence of shales which crop out only in rare places. (Map, fig. 11 and Pl. XXXVII).

The first ridge is the most constant of all in its physical features. It stands out boldly, but is not sharply crested and has a peculiar more or less hummocky outline (Pl. II, fig. 1). It is composed of coarse, gritty quartzites representing the Government Reef Quartzites and grits of the Witwatersrand. It can be followed from Witbank towards the south over Schurvedraai and Mooiplaats a long distance; north of the Vaal River it is well developed on Koedoeslaagte, Rietpoort and Brakfontein.

The two remaining quartzite-ranges belong respectively to the upper portion of the Government Reef Series and the Main-Bird Reef Series; they are not conspicuous in the landscape, especially some distance away from the Vaal River. The slates in the valleys between these ranges of hills are more or less ferruginous.

Beyond the third quartzite-ridge, which stands out well along the left bank of the Vaal River from Schurvedraai downstream, a broad valley stretches in which the Vaal River flows from Schurvedraai as far as Schoemansdrift. Soft shaly rocks occupy this valley. Their strike is not exactly coincident with the trend of the valley. The latter valley can be followed in a north-easterly direction from Koedoeslaagte over Koedoesfontein and further, being faulted towards the north, over Witkop towards the Vaal River, and may be said to indicate the position of the Kimberley shales. Its characteristic features are lost in the landscape a small distance south of the Vaal River, in the western portion of the area south of Reitzburg, in the eastern portion on Palmietfontein. Beyond this broad valley follow in a wide curve (see map) a series of broad ridges composed of quartzites, conglomerates and grits. A fine section through this complex of rocks is visible along the southern bank of the Vaal River on Elandslaagte where that stream below Schoemansdrift cuts it at right angles. This complex represents the uppermost portion, the Kimberley-Elsburg Series, of the Witwatersrand System.

4. The Ventersdorp System.

Another semicircle of hills, in some places rising to greater heights than any of the other hills in the district, follows outside the belt of Witwatersrand Beds. These hills are characterised by smooth dome-shaped outlines and the absence of prominent features. They are treeless, grass-covered and, seen near by, look barren and desolate. They are chiefly composed of diabase forming a huge flow, which is amygdaloidal at most places, and of diabase-porphyrite. The amygdaloidal diabase passes into porphyrite in the deeper portion of the big flow.

5. The Transvaal System.

Outside of this girdle follow the beds belonging to the Transvaal System (see Map).

The *Black Reef Series*, at the base of this system, is feebly developed. Where well visible, it is composed of some strata of quartzite and shales and as a rule it also contains one or two layers of conglomerate, the entire thickness nowhere exceeding 15 m. In many places it appears to be wanting between the amygdaloidal diabase and the (stratigraphically) overlying dolomite. Probably at such localities the outcrop is hidden by surface-soil.

The *Dolomite* is well developed, but its overtilted or vertical position and deep weathering rarely lead to good outcrops. De Wets Drift, where the dolomite is tilted at right angles, affords at low water an exceptional opportunity to measure in the bed of the Vaal River the entire thickness of this series as well as that of individual layers of dolomite and interbedded chert. The upper portion is much richer in chert than the lower, and also contains peculiar crush-breccias. The thickness of the dolomite-belt at De Wets Drift is at least 550 m. [1])

Beyond the dolomite follow the *Gatsrand Beds*, of which only the lowermost portion forms a distinct curved girdle, the most remote one around the Vredefort granite. In the upper portion no curved trend of the outcrops exists. This is caused by the fact that only the lowermost strata of this series are involved in the overtilting of the sediments round the Vredefort granite; higher in the series, i.e. further from the granite, the normal non-overtilted position of the strata is soon resumed and the uppermost division

1) G. A. F. Molengraaff, **58**, p. 266.

is not tilted at all, and is responsible for the Table Mountain features of the proper Gatsrand.

6. The Karroo System.

Unconformably and horizontally overlying all the older formations are coal-bearing deposits of the Karroo System (see Map and fig. 1 and 2). They were deposited long after the period during which the disturbances took place that gave rise to the characteristic features of the Vredefort Mountain Land. A long period of denudation lies between the time of the uptrusion of the Vredefort Granite with the accompanying tilting of the surrounding sediments and the deposition of the Karroo Beds. The latter were laid down after the Vredefort Granite had been laid bare by the removal of thousands of meters of sediments which covered it. The surface on which the strata of Karroo age rest is uneven, undulating within the granite-area, and bolder of relief within the belt of highly tilted sediments around the granite. The unevenness of this surface combined with the fact, that the Karroo Beds themselves have later been denuded away to a great extent, explains why the latter show a great variability in thickness in the Vredefort area and are often absent.

The lowermost division of the Karroo System — the Dwyka Tillite Series — has not yet been found in this area, though it is highly probable that it will occur at the base of the System. The Ecca Beds and specially sandstones, shales, coal-measures and dolerite, all belonging to the Middle Ecca Series, are well developed. Casts of Sigillaria are found in the sandstone and associated Coal Measures. In 1922 on the farm Wonderfontein south-east of Vredefort several prospecting shafts had been sunk revealing a coal-layer at a depth from 18 to 25 m. Several fairly well preserved casts of Sigillaria were found there by the authors. In the landscape the dolerite which forms sheets in the Coal Measure group is much in evidence and by its fairly great resistance to weathering is rather conspicuous in many places, as e.g. at the Inlandsche Zee, on the farms Essex and the southern portion of Wittepoort, near Dover Station, and at several other localities.

7. The Marginal Intrusions.

a. *Dykes, Boss-like Dykes and Sills of Gabbroid Rocks at or near the Periphery of the Granite.*

In the granite, at or near its periphery, numerous bodies of gabbroid rocks have been injected. These intrusions took place, as shown later, during and after the updoming of the granite and the surrounding sediments. The most important of them occur in the shape of a marginal belt situated as a rule at a short distance from the edge of the granite, and indicating the position of a marginal fissure. This belt is not quite continuous, the intrusions being somewhat localised at certain spots where conspicuous, steep black hills or kopjes (Pl. V, fig. 1 and 2) now stand out, usually encircled on all sides by the granite, but always close to the periphery of the latter. These kopjes are generally elongated in a tangential direction and often run out in that direction into narrower dykes (Kopjeskraal).

Fig. 3.

Ideal Section across granite-margin to illustrate the sill-like character of some of the interior basic marginal intrusions. 1. Vredefort Granite, 2. Gabbro and epidiorite, 3. Basal Amygdaloid, 4. Orange Grove Quartzites, 5. Ferruginous hornfels = Altered Water Tower Slates.

While these kopjes thus in some places represent the cross-sections of broader, boss-like portions of a peripheral dyke, at other places they are parts of sills or sill-like bodies (fig. 3) dissected by erosion, which from the peripheral dyke or dykes were injected along more or less horizontal fissure-planes into the granite in a radial direction or in the opposite direction into the surrounding sediments as well, as occurs for example on Brakfontein (fig. 6).

This variation in the form assumed by the basic marginal intrusions is of great significance in the tectonic history of our area ; it rests on the evidence of distribution in the field, and also on the manner in which the selvage-phenomena are disposed, as exemplified in Fig. 4 and Fig. 5.

Fig. 4 represents the relationship seen on Anna's Rust. At the contact

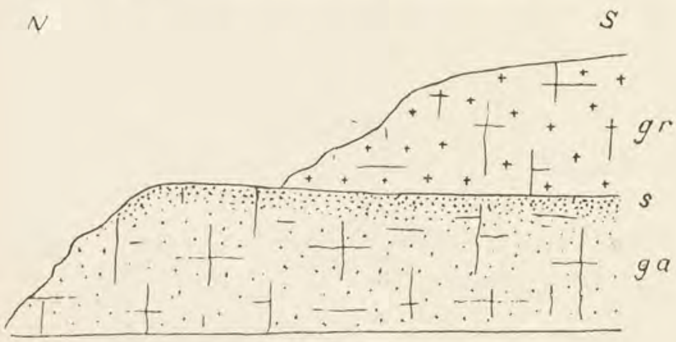

Fig. 4 and 5.

Sections across the contact between gr. granite and ga. gabbro showing the gradual development of selvages denoted by closely packed dots in the gabbro at s. Approx. scale 1 : 60.

Fig. 4. Sill of gabbro on Anna's Rust with horizontal selvage.

Fig. 5. Dyke of Gabbro on Witbank with vertical selvage.

between granite and gabbro, the latter makes a very slightly inclined little shelf or platform (nearly horizontal) which passes under the granite. The increasingly finer grain as one approaches the granite, is well marked and finally leads to an extremely close-grained selvage, disposed with reference to the sensibly horizontal plane of contact. This relationship points to the gabbro having a sill-like character, a conclusion supported by the fact that the line of contact does not run straight across country, but almost coincides with a contour-line.

On the other hand, on Witbank, at the northern foot of the little gabbro-kopje near the school (Plate V, fig. 1), the contact is as shewn in fig. 5.

The selvage is now disposed with reference to a vertical plane of contact, and its trace runs across country in a more or less straight line. The gabbro, therefore, has the form of a dyke.

Such marginal gabbro-kopjes lie (from west to east) on Driehoek and Rietkuil, Witbank, Kopjeskraal, Rietpoort, Brakfontein, Anna's Rust, Zandfontein and Tweefontein ; in the south-eastern portion of the area others may exist concealed by rocks of the Karroo System and others again may be found in localities not visited by the authors.

Where these kopjes represent broad boss-like portions of dykes they are covered with boulders of different and often large sizes in chaotic confusion, as can be well seen in the kopjes on Witbank and Kopjeskraal and again in the Twinkopjes (Pl. V, fig. 2) on Old Rietpoort ; where they represent portion of sills they show three systems of joints, one horizontal or nearly horizontal and two vertical at right angles one with the other, thus forming a structure known as a Cyclopean Wall, so well observable at many places in fairly flat-lying norites and pyroxenites belonging to the igneous complex of the Bushveld. Such a structure is beautifully developed in the gabbro-sill behind the school on Anna's Rust (Pl. VI, fig. 2) and in that on Tweefontein near the boundary with Weltevreden (the outcrop of the latter is not indicated on the map).

A rather extensive sill is cut in two by the Vaal River, where it enters the granite-area between Brakfontein on the Transvaal side, and Anna's Rust on the Free State side. In the Orange Free State this sill is well exposed

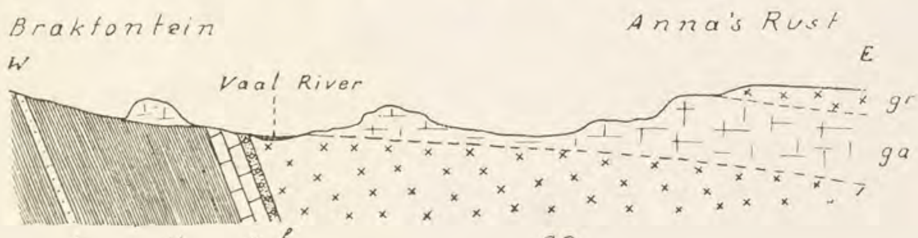

Fig. 6.

Sill of Gabbro on Brakfontein and Anna's Rust. gr. granite, ga. gabbro, *b*. Basal Amygdaloid, o. Orange Grove Quartzites, *w*. Water Tower Slates, *s*. Speckled Bed.
Length of Section 3 km.

on Anna's Rust (Fig. 6), where it has a thickness of at least 47 m. and dips with a slight angle away from the river. In the escarpment east of the school and of the road the gabbro can be well seen to be covered by granite underneath which it disappears with a slight dip towards south-east; the gabbro obviously fills a nearly horizontal fissure, and thus forms an intrusive sheet or sill in the granite. On the Transvaal side of the Vaal River the same sheet is represented by a kopje on Brakfontein, which not far from the right bank of the river is connected by a strip of low-lying gabbro-country with another hill on Rietpoort, called Liebenberg kopje (Pl. VI, fig. 1). The latter standing isolated and being almost entirely encircled by low-lying granite-country is rather representative of the features of these gabbro-kopjes.

This sill starting from the main vertical peripheral fissure is on the Transvaal side of the river not only injected into the granite in the direction of Liebenberg kopje but also in the opposite direction into the sediments after their tilting. Hence at the kopje on Brakfontein the gabbro rests nearly horizontally on the edges of the uptilted strata of the Orange Grove Quartzites and the (stratigraphically) overlying ferruginous and garnetiferous slates (metamorphosed Water Tower Slates) which dip at an angle of 76° towards the granite (fig. 6).

The Brakfontein—Anna's Rust sill is the largest of this class of intrusions in the entire area and before its dissection by erosion it must have formed a flat-lying intrusion covering at least 12 square km.

Other good examples of sills are found on Tweefontein near the boundary with Weltevreden and again on Rietkuil. In the kopje on the latter farm near Rensburg's homestead the gabbro-sill is clearly covered by granite and probably the visible portion only represents a fraction of its former extent.

In some instances the gabbroid rock, being intruded at the very edge of the granite, encroached in a radial direction upon the lowest portion of the adjacent Witwatersrand Beds. Thus on Zandfontein at the northern boundary of the farm a small boss-like dyke of gabbro invades the Orange Grove Quartzites.

On Tweefontein the same thing happens and since the basic intrusion found there is of particular interest it is treated seperately in some detail.

The Tweefontein Boss and its Hybrid Rocks.

On Tweefontein 385 near the homestead a small boss of gabbroid composition has been intruded at the very edge of the granite. Its field-relations are represented in fig. 7.

The dimensions are 224 m. along the strike of the sediments and 377 m. in the direction at right angles to the strike. The intrusion cuts across the ferruginous Water Tower Slates and the underlying thin band of a quartzite, the speckled bed, the surface of which is pitted due to the removal of crystals of decomposed felspar. The thickness of the ferruginous slates is 170 m. and of the felspathic quartzite 1.2 m. Below the latter some diabase, probably a sill, is found, and underneath it some distance towards the south-east the Orange Grove Quartzites, which, on the other side of the road leading to Vergenoeg, form a conspicuous ridge trending in a south-easterly direction towards Zijferfontein. The sediments and the intrusive sill between them are highly tilted and on an average dip 87° towards the south-east i.e. towards the granite. The ferruginous slates and the felspathic quartzite are clean cut off by the intrusives of the small boss, the contact between the two rocks being very well defined in places. The north-western portion of the intrusion, where it abuts against a large sill-like intrusion of epidiorite above the Water Tower Slates is much sand-covered and not well seen. A small detached offshoot of the boss crops out again some distance to the north of the main mass. Grass-covered subsoil also hides the opposite end of the gabbroid intrusion, where it cuts across the Orange Grove Quartzites and is probably in contact with the granite.

Many xenoliths of Orange Grove Quartzites and Granite caught in the intrusive rock prove that the magma must have forced its way towards the place where it is now found, both through the granite and those quartzites.

Close to its margin the grain of the intrusive rock becomes finer and shows all the characteristics of a selvage.

After the consolidation of the rock of the boss another gabbroid magma was intruded as a sill in between the strata of the Water Tower Slates (see fig. 7). It also cuts across the intrusive boss itself, maintaining all the while the average thickness of 45 m., which it has between the slates. It possesses a well marked fine-grained selvage in contact both with the Water Tower Slates and with the intrusive rock of the boss. Much later a fault at right angles to the strike of the sediments has thrown the block north-west of the boss about 94 m. to the south. The fault runs almost exactly along the western contact of the boss but has just cut of a small slice of its extreme northern portion.

The Hybrid Rocks of the Boss. All over the boss, but unequally distributed, the intrusive rock carries xenoliths, among which those of Orange Grove Quartzite and of Vredefort Granite are easily recognised. The latter xenoliths are mostly well rounded and often ball-shaped; small fragments from a few mm. to two cm. in diameter are very frequent, but larger ones up to 10 cm. are not rare. One unusual large xenolith of granite deserves special attention. It occurs in the eastern portion of the boss and has a length of about 15 m. and a width of about 9 m. It is composed of a distinctly gneissic reddish granite showing several nests and veins of equally reddish pegmatite. The xenoliths of quartzite are irregular in shape but always rounded at the edges. The largest one observed (Pl. XVI, fig. 1) measured fully 50 cm. in its greatest diameter; smaller fragments are very numerous.

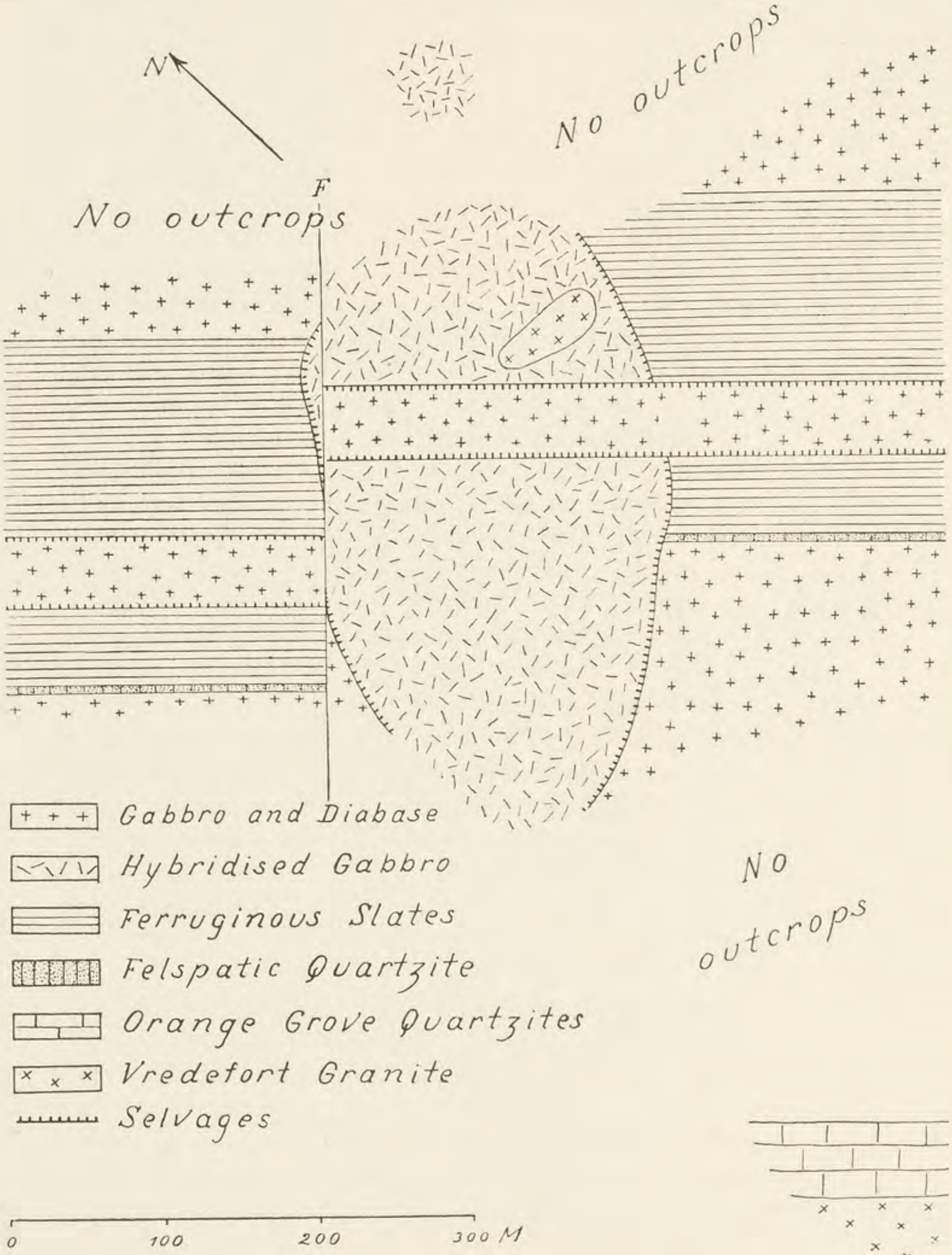

Fig. 7.

The boss of hybridised gabbro on Tweefontein 385.

The composition of the gabbroid rock of the boss has been greatly altered and acidified by the incorporation and assimilation of many fragments of granite, quartzite and probably also of ferruginous shales, although xenoliths of the latter were not observed. The general effect of the assimilation of the xenoliths of granite and quartzite has been such that the mother-liquor was pushed onward along its normal crystallisation-course [1]), that the cooling has been hastened, that crystals of the minerals with which the gabbroid magma was saturated when the xenoliths were incorporated, viz. amphibole and some biotite, were precipitated, and the amount of granitic differentiate crystallising as micropegmatite greatly augmented.

Consequently the rock is no more a gabbro now, but a hybrid rock, or rather a complex of several hybrid rocks.

With the naked eye reaction-rims can be distinguished round the inclusions of quartzite and with a pocket-lens a granophyric structure is well seen in the more strongly altered varieties.

The different hybrid rocks merge into one another, but for the sake of convenience the following types may be singled out, ranged in ascending order, according to the degree of acidification and divergence from the original gabbroid rock.

Type 1. This type of rock is predominant in the entire central portion of the boss and is especially well developed in its southern part. It is the main type.

Macr. A moderately coarse rock, containing numerous xenoliths of quartzite and granite, frequently of large size. The largest inclusions of quartzite which happened to be observed, were found in this rock (Pl. XVI, fig. 1). Long black crystals apparently of amphibole (in reality imperfectly uralitized diallage) are prominent and between them reddish felspathic matter is well seen. The rock has a syenitic appearence. With a pocket-lens the feldspathic matter is seen to consist of rather long, well-defined, grey, semi-pellucid crystals of plagioclase and abundant reddish patches of irregular shapes, showing clearly a granophyric structure.

Micr. The original non-typical ophitic structure of the gabbro is fairly well preserved (Pl. VII, fig. 1). Primary constituents: Typical diallage (somewhat uralitized), basic plagioclase, both fairly idiomorphic in rather large crystals, ilmenite, sparsely yellowish-brown biotite. The crystals of plagioclase often enclose those of diallage and in such cases the two minerals are frequently regularly intergrown, the diallage forming a well-marked graphic structure within the crystals of plagioclase.

Xenoliths. Quartzite and granite.

New formed minerals. Green amphibole, biotite showing pleochroism from yellowish to brown-green, and abundant micropegmatite growing out from all the primary minerals but mainly from the felspars (Pl. VII, fig 2).

1) N. L. BOWEN. 6, p. 559.

The xenoliths of quartzite are surrounded by well-defined rims of deep-green amphibole (Pl. VIII, fig. 1); those of granite have no reaction-rims. Crystals of the new-formed green amphibole sometimes occur well within corroded crystals of plagioclase. A second generation of acid felspar allied to albite is not formed as is the case in the next type.

Type II. It is found best developed at the extreme north-eastern edge of the boss.

Macr. Rock moderately fine-grained. It contains numerous xenoliths, mostly of small size, of quartzite, of granite and of fragments of disintegrated granite. The colour is greyish, where only xenoliths of quartzite were incorporated, but passes into pinkish where xenoliths of granite begin to predominate.

Micr. Original gabbro-structure partly obliterated, partly fairly well preserved. Diallage in places uralitized; basic plagioclase in large, fairly stout crystals, rather decomposed.

Xenoliths. Quartzite surrounded by a reaction-rim, on the average ¼ mm. thick; minerals of the granite, viz. orthoclase, plagioclase, biotite, quartz, either scattered or still coherent. Some of the xenoliths of felspar with crossed nicols are resolved into an aggregate of grains each of which shows a honey-combed or cellular structure which appears to belong to a peculiar variety of micropegmatite.

New-formed minerals. Amphibole, green and strongly pleochroic, in rims around the quartzite-xenoliths, also scattered in the granophyre, and sometimes in great quantities within partly absorbed xenoliths of felspar. This amphibole is very different in appearance from the uralite, which has partly replaced the diallage. Its pleochroism is: $\mathfrak{a}$ = pale, yellowish green; $\mathfrak{b}$ = dark, brownish green; $\mathfrak{c}$ = rich olive-green. Biotite occurs together with the green amphibole, but in much smaller quantities. The amphibole and the biotite both show pleochroic halos. A second generation of plagioclase is found in lath-shaped crystals evidently continuing the growth of felspars, which was going on in the gabbro-magma before the xenoliths became incorporated and the magma became acidified. They are perfectly fresh and simply twinned according to the albite-law; their angle of extinction as well as their index of refraction prove them to belong to an acid plagioclase, either albite or a closely allied type.

Granophyre (micropegmatite) abundant, principally growing out from the fresh felspar-laths just mentioned. These laths are frequently surrounded by a narrow rim which imperceptibily merges into and has the same extinction as the quartz-component of the micropegmatitic intergrowth. Near a lath of felspar from which it expands such an intergrowth often has a myrmekitic, thread-like structure, but passes some distance from it into an ordinary coarser micropegmatite (Pl. VII, fig. 3 and 4).

This type II is closely allied to type I. Its smaller grain as compared with rocks of type I is caused by the more marginal position of the rock and is a selvage-phenomenon.

Type III. It occurs exclusively, where xenoliths of granite are very abundant and is found in the south-western portion of the boss and again at its northern edge in close connection with rocks of type II.

Macr. Colour pink, resembling a granophyre with cognate inclusions of granite.

Micr. The original gabbro-structure is, with the exception of some spots, quite obliterated, evidently by the incorporation of much material from the granite. Hardly any femic minerals are left, except some more or less altered flakes of biotite derived from the incorporated granite. In fact primary constituents are only found at rare spots where some altered diallage and plagioclase have survived.

Xenoliths. Abundant inclusions of granite and its scattered minerals: orthoclase, plagioclase (both not well idiomorphic), biotite and quartz, and also some of quartzite.

New formed minerals. Abundant micropegmatite growing out from all the crystals of felspar. Green amphibole especially in more or less well-marked rims around the xenoliths of quartzite.

Had this rock been found by itself, it would have been taken for a granophyre, i. e. for a granitic rock.

Type IV. This type is represented by the large xenolith of gneissic granite marked on the sketch fig. 7.

The microscope shows all the minerals of the granite surrounded by and thus separated one from the other by broad rims of micropegmatite, which probably has been formed by a reaction between the component minerals of the granite, set in after the incorporation of the xenolith in the gabbroid magma, and possibly stimulated by the juices emanating from the magma and penetrating into the more or less disaggregated granite.

Type V. This type of rock consists of coarse grains, each of which have a granophyric structure. It is found in the south-western part of the intrusion. The behaviour of some of the xenoliths of felspar, found e.g. in rocks of type II offers an explanation of this peculiar type. The felspars of these xenoliths, as has been pointed out above, are entirely altered into a kind of mosaic, the composing particles or grains of which all possess a granophyric structure. This type V is probably a xenolithic felspathic rock which has been altered into a peculiar coarse-grained granophyric rock by the influence of the molten gabbroid material in which it had been incorporated.

The sill of gabbro. This sill, which is intercalated about midway between the ferruginous Water Tower Slates and also cuts dyke-like across the Tweefontein boss, (fig. 7) was intruded at a time, when the hybridisation of the originally gabbroid rock of the boss was completed. Moreover the latter had already been sufficiently cooled to cause a more rapid cooling of the sill at the contact. Consequently a well marked selvage is found at the margin of the sill.

From the centre up to about two or three feet from its margin the sill consists of a fairly coarse typical gabbro-diabase, the diallage of which is uralitised to a small extent. In places it is somewhat porphyritic through scattered large phenocrysts of pale green plagioclase. Some micropegmatite represents the latest product of crystallisation, not, however, in much greater quantities than is often found in not too rapidly cooled gabbros or diabases.

The marginal portion is fine-grained, as belongs to a selvage. This particular marginal rock, however, is characterised by the presence of micropegmatite in abundance, which occupies a considerable part, estimated at 20 % of the entire bulk of the rock ; consequently in places this marginal rock bears a great resemblance to some varieties of the hybrid rock of the boss, in which xenoliths are not much in evidence [1]). Thus the marginal portion of the sill is not a pure gabbro any more, but a much acidified derivative, indeed a kind of hybrid rock. The explanation appears to be as follows.

This sill, forcing its way through the hybrid rock of the boss, which was already perfectly consolidated and more or less cooled, took up, in its turn near its margin some fragments of this acidified hybrid rock, which gave rise in the magma of the sill near the contact to the same kind of reactions which took place on a much larger scale in the gabbro (now hybrid rock) of the boss or tongue, at the time the latter took up fragments of Old Granite, quartzite etc. Thus it is easy to understand that the marginal portion of the gabbro of the sill, being in its turn converted into a hybrid rock, must now show, in an attenuated way the same types of structure as are found in the hybrid rocks of the Tweefontein boss itself.

Some of the intrusions of gabbroid rocks occur at a somewhat greater distance from the periphery of the granite.

Thus at Kafferkop, about 3 km. south of Parijs a broad dyke-like intrusion of diabase occurs showing some hybridisation by incorporation of foreign material, probably of granite. Kafferkop is situated 7 km. away from the nearest point of the granite-periphery.

A big dyke runs from Kafferkop in a N.W.-S.E. direction through the farm Groot Eiland right into the farm Lesuto's kraal where it appears to stop. This dyke has a width of 60 m. and consists of gabbro-diabase.

On the Parijs Commonnage another powerful dyke of typical gabbro occurs ; it runs from the weir above the township in a south-southeastern direction, slightly curving eastward; it disappears south of the Parijs—Dover Railway underneath surface-soil, and may extend further below the overlying beds of the Upper-Karroo. This dyke was first described by SHAND [2]) who gives it a width of 600 yards (552 m.) near the weir. We have not been able to follow it on the Transvaal side of the Vaal River and

1) Outside of the boss, in between the ferruginous slates, the fine-grained selvage of the same sill also contains micropegmatite, but in a considerably smaller proportion.

2) S. J. SHAND, **85**, p. 208.

although, as seen from the Parijs Commonnage, the strike of the dyke points towards Liebenberg kopje, we could not find its extension there.

On Smalfontein near the homestead a thin dyke occurs quite near the periphery of the granite. It consists of greatly uralitized gabbro.

On Rietpoort north of Parijs a dyke cuts the granite at a distance of 3 km. from the periphery; it is composed of a hyperite much resembling the rock of the sill on Rietkuil.

On Vleispruit 889 a dyke 110 m. wide crops out over a considerable distance, at a point somewhat more than a mile distant from the periphery of the granite. It is a somewhat amphibolitised gabbro. On the farm Enkeleboom at the boundary with Broodkop about 8 km. from the edge of the granite, a dyke of very fresh and typical gabbro cuts both granite and gneiss.

The authors do not know of any occurrence of gabbroid intrusions in the granite situated in a more central position than those enumerated here, which appears to prove that all the gabbroid intrusions in the granite took place at or near its periphery, and suggests some causal relation between the updoming of the granite, i.e. the process which fixed the outlines of the granite-boss, and the intrusions of the gabbroid rocks.

The gabbroid rocks of the marginal intrusions comprise the following types:

O l i v i n e-g a b b r o. The component minerals are augite, olivine and plagioclase as main constituents, and a strongly pleochroic biotite and ilmenite as subordinate constituents. The texture is ophitic and the crystallisation of the plagioclase must have commenced at an early stage of the process of consolidation, laths of plagioclase being found enclosed in all the other minerals, the ilmenite not excepted. Some micropegmatite is wedged in between the other minerals as an end-product of crystallisation. We have found olivine-gabbro exclusively in the Transvaal portion of the large Brakfontein-Anna's Rust sill i.e., in the kopje on Brakfontein and in Liebenberg kopje. The rock is found here in a perfectly fresh condition. At the latter locality it is richer in olivine than at the former.

G a b b r o. The gabbro closely resembles the olivine-gabbro in mineralogical composition and texture, but is free from olivine. The fact that the large Brakfontein-Anna's Rust sill is free from olivine at the Free State side of the Vaal river, but carries olivine at the opposite side, proves that the olivine-gabbro has to be regarded as a local variety of the gabbro. No corroded relics of olivine were found in the olivine-free varieties. In this gabbro a granophyric intergrowth of ilmenite and biotite is frequently observed. By gradual changes in texture the gabbro in places passes into varieties, which must be called gabbro-diabase and diabase.

The chemical composition of this gabbro on Anna's Rust is, from an analysis made by H. G. WEALL, Government Laboratories, Johannesburg, as follows :

SiO_2	51.7
TiO_2	1.35
ZrO_2	—.—
Al_2O_3	14.4
Fe_2O_3	3.3
FeO	9.5
MnO	—.—
CaO	9.75
MgO	7.6
Na_2O	2.15
K_2O	0.55
P_2O_5	nil
CO_2	—.—
Loss at 100°	0.2
Loss on ignition	0.05
	100.55

Sp. Gr. 2.98.

The following intrusions in the granite or at its edge are composed of gabbro or gabbro-diabase:

The dyke on Waarom ;

the sill on Vechtkop ;

the Free State portion of the Brakfontein-Anna's Rust sill east of the school on Anna's Rust ; the gabbro of this sill shows a finer-grained selvage (fig. 4) against the granite-roof, which in texture corresponds with diabase or dolerite ;

the boss-like intrusion on Zandfontein, where the gabbro has invaded the Orange Grove Quartzites. The gabbro at this occurrence contains more micropegmatite as the last product of crystallisation than at any other locality. This may have been caused by a certain amount of acidification of the magma consequent on assimilation of some of the invaded quartzite. We failed to observe xenoliths of quartzite in the gabbro at that spot, but our search was not exhaustive ;

the thin dyke on Smalfontein, where the rock is somewhat decomposed and uralitised, and carries an unusually great amount of ilmenite which mineral stands out on the weathered surface ;

the boss of Kafferkop 5 km. from Parijs, where the gabbro is somewhat decomposed ;

the powerful dyke on Groot Eiland running from Kafferkop in a N.W.-S.E. direction. This gabbro-diabase shows cataclastic structure and is somewhat uralitised ;

the big dyke on the Parijs Commonage, where the gabbro is beautifully fresh and shows exquisite ophitic texture ; [1])

1) S. J. SHAND, **85**, p 208. SHAND calls this rock quartz-dolerite, but we think gabbro is the proper name, because quartz is only found in the micropegmatitic residual magma.

the dyke of diabase on Broodkop, in which the crystals of plagioclase are dusty and yellowish.

Norite. On the north-eastern portion of Zijferfontein and on the adjoining south-western portion of Vergenoeg a beautiful poikilitic norite occurs as a marginal intrusion at the edge of the granite. Large phenocrysts of plagioclase measuring in the direction of the axis *c* up to 26 mm. the cleavage-planes of which give to the rock a typical facetted lustre, are inbedded in a finer-grained mass composed of plagioclase, rhombic pyroxene and some ilmenite. Here and there a rest-crystallization of micropegmatite is seen wedged in between the other elements. The large phenocrysts of plagioclase enclose scattered crystals of pyroxene and some ilmenite. Throughout the rock the rhombic pyroxene is crystallized in plump well idiomorphic prisms bounded chiefly by the two vertical pinacoids {100} and {010} slightly truncated by small faces of the prism {110}. The plagioclase is coloured by a yellowish to brownish pigment and shows twinning both after the albite and after the pericline law. The pyroxene is to a considerable extent altered into actinolite, the crystals of which are irregularly interwoven; notwithstanding this the crystal-form of the pyroxene is still well preserved. A fair proportion of the pyroxene is still unaltered, the plagioclase is little attacked; titanite and zoisite are not present, and thus the rock shows an early stage of the process of epidioritisation.

Pyroxenite. Not far from the place where this poikilitic norite occurs an outcrop is found of a pyroxenite. This rock is medium-grained and composed chiefly of stout prisms of rhombic pyroxene, probably enstatite, and sparsely also contains some laths of a brownish pigmented plagioclase. The texture is not ophitic, as could be expected from the great preponderance of the pyroxene over the felspar. The rock is perfectly fresh. The crystals of rhombic pyroxene show in places a narrow rim of monoclinic pyroxene. Actinolitic amphibole is not present.

Hyperite. This variety of gabbro contains large somewhat resorbed phenocrysts of rhombic pyroxene besides smaller crystals of monoclinic pyroxene. It is found in the sill on Tweefontein near the boundary of Weltevreden, and in the boss-like dyke between Oud Rietpoort and Klein Rietpoort at the foot of the Twin-kopjes. The rock contains at the latter locality a dusty yellowish variety of plagioclase. The selvage of this rock against the surrounding granite has a smaller grain and is a gabbro-diabase without rhombic pyroxene. Hyperite also occurs in the sill in granite near Rensburg's homestead on Rietkuil.

These basic marginal rocks within the granite often show epidioritisation in various stages. In the writers' opinion it is a conclusion of genetic significance, that these changes are practically indistinguishable from those found in the basic marginal rocks within the Lower Witwatersrand Beds, where they are highly characteristic features. The *modus operandi* is discussed in some detail in the next section which deals with the epidiorite found as sills in the encircling sediments.

b. *Sill-like Dykes of Epidioritised Gabbroid Rocks in the lower portion of the Lower Witwatersrand Beds.*

In the Vredefort area some persistent sills and sill-like dykes of gabbroid rocks occur in the lower portion of the Lower Witwatersrand Series.

The outcrops of these sills are generally marked by the presence of a profusion of boulders of moderate dimensions provided with a deep red-brown weathered coating ; where hidden, they are not seldom betrayed by the deep-brown colour of the surface-soil.

These intrusives have a similar composition throughout the entire area, all consisting of gabbroid rocks, which are either entirely or to a large extent converted into epidiorite. Although over considerable distances they appear to be intruded like simple sills into definite horizons of the Witwatersrand Beds, at other places they cut across the sedimentary beds, send out offshoots, anastomose with each other and behave like more complex intrusions, invading and apparently disturbing the sedimentary beds. (Pl. XXXVIII, and fig. 8).

1. The most important of these intrusions occurs on the western portion of Rietpoort (i.e. the portion west of the main road from Parijs to Potchefstroom) as a thick sill (360 m.) between the third and the fourth bar of quartzite (fig. 9 and Pl. IV, fig. 2) of the Orange Grove Quartzites. More to the west towards Kopjeskraal the intrusion cuts across the lowermost band of the Orange Grove Quartzites and further on Kopjeskraal is found stratigraphically below the Orange Grove Quartzites either between them and the Basal Amygdaloid or right in the Basal Amygdaloid itself (Pl. XXXVIII) losing much in thickness. Still further to the west and southwest its continuation is found on Witbank as a narrow sill between the third and the fourth bar of the Orange Grove Quartzites. Its thickness there is about 6 m. Following the same intrusion towards the east we see it affected by the transverse fault at the main road on Rietpoort, by which the Water Tower Slates are displaced towards the south about 270 m.

The rocks of this intrusion are epidiorites, and conform to the third and fourth stages of the process of epidioritisation of the marginal gabbroid rocks in the granite as given below. Small flakes of biotite are frequent in the rock of the sill, and in this respect they differ from the rocks of the marginal intrusions in the granite, in which biotite is rare. For the rest both in texture and in mineralogical composition the epidiorite of this sill in or near the Orange Grove Quartzites resembles so closely the epidiorite of the marginal boss-like dykes in the granite e.g. on Kopjeskraal and Witbank, that slides of both these species of rocks are well-nigh indistinguishable from one another. In both types the ophitic texture has disappeared in several instances and then a granulitic texture (*Mörtelstruktur*) has

taken its place, the rock making the impression of being minutily shattered.
The chemical composition of this rock is as follows :

SiO_2	52.5
TiO_2	1.15
Al_2O_3	10.5
Fe_2O_3	4.5
FeO	9.65
CaO	10.95
MgO	7.25
Na_2O	2.3
K_2O	0.2
P_2O_5	0.1
Loss at 110° C.	0.2
Loss on ignition	0.6
	99.9

Sp. Gr. 2.95.

Epidiorite on Rietpoort. Analysis by H. G. WEALL, Government Laboratories, Johannesburg.

2. Another intrusion of more complex character is known to occur in the Lower Witwatersrand Beds on Weltevreden, Tweefontein, Vergenoeg and the north-western portion of Zijferfontein. It has been described and carefully mapped by PENNY [1]).

PENNY describes its character as follows : ,,This intrusion has burst through the sedimentary rocks, intruded tongues along lines of weakness in them, caused extensive faulting, and broken through thick beds of quartzite at right angles to the strike, thereby completely isolating several large and small masses of quartzite and slate". This intrusion now covers a considerable stretch of country (Fig. 8). An offshoot of this intrusion having the shape of a sill in the ferruginous Water Tower Slates cuts as a dyke across the boss of hybridized gabbro near the homestead on Tweefontein(Fig. 7).

The rock of this big intrusion consists of a somewhat amphibolitised gabbro, characterized by the peculiar dusty appearance and yellowish colour (in the slide) of the plagioclase. The pyroxene of the gabbro is only partly replaced by actinolite and the ophitic structure is well preserved. Ilmenite is present and both titanite and zoisite are absent. The rock offers a good example of the first stage of epidioritisation of gabbroid rocks, as given below.

1) F. W. PENNY, **66**, with map.

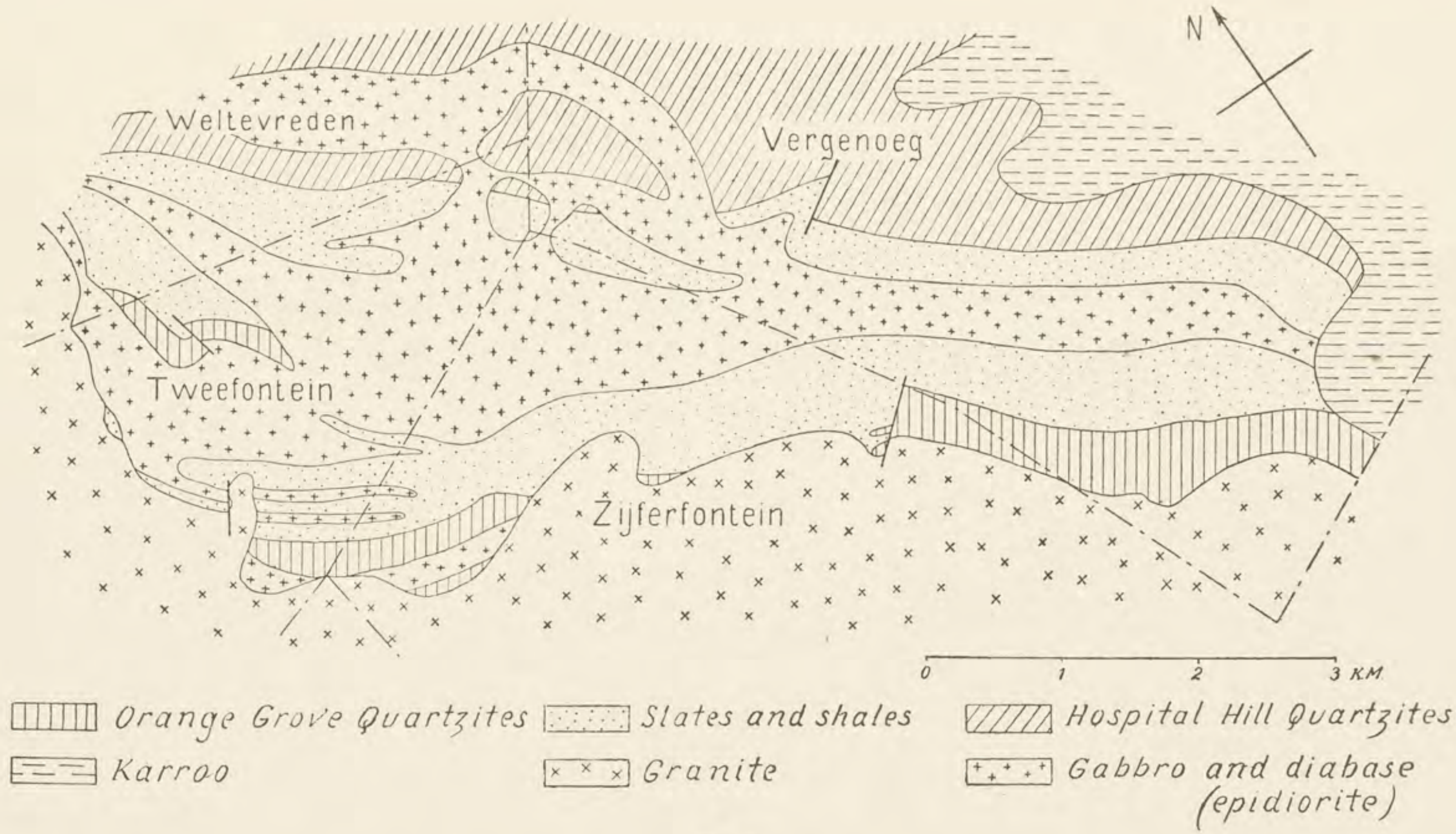

Fig. 8.

The large basic intrusion in the Lower Witwatersrand Beds near the edge of the granite on Tweefontein. This sketch is a simplified copy of PENNY's sketchmap. PENNY's conception has been left unaltered, and accordingly the small boss of hybridized gabbro on Tweefontein (fig. 7) is shown here as an offshoot or tongue of the Vredefort Granite intruded in the lowest portion of the Witwatersrand Beds.

The chemical composition of this rock is as follows :

SiO_2	51.65
TiO_2	0.95
Al_2O_3	14.6
Fe_2O_3	0.3
FeO	11.1
CaO	9.85
MgO	6.95
NaO	2.65
K_2O	0.65
P_2O_5	0.1
Loss at 110° C.	0.25
Loss on ignition	1.0
	100.05

Sp. Gr. 2.96.

Gabbro, Tweefontein. Analysis by H. G. WEALL, Government Laboratories, Johannesburg.

3. A third intrusion is found as a sill in the metamorphosed ferruginous shales overlying the Orange Grove Quartzites. The authors noticed it on Leeuwdoorns and on Witbank, and again on Wittepoort. The offshoot of the big intrusion on Tweefontein mentioned above occurs in the same horizon and thus at this locality the intrusions distinguished as 2 and 3 are probably connected.

4. A fourth intrusion occurs as a rather persistent sill in between the strata of hornfels a short distance below the horizon of Lower Green Quartzite and in many places has a conspicuous outcrop marked by accumulations of irregular boulders on which clusters of shrubs grow. It is well developed on Witbank and on Kopjeskraal where it attains a thickness of 25 m.

From Kopjeskraal it keeps in easterly direction the same horizon towards Rietpoort and probably is connected with the offshoot of the big sill near the fault on Rietpoort, mentioned above. If this might be so, it becomes evident that the sills in the Lower Witwatersrand Beds are connected in more than one place and probably form together a system of marginal intrusions just outside the periphery of the granite, representing one simple intrusion or a couple of intrusions closely connected in character and in age. In contradistinction to the marginal intrusions inside the contact, between the sediments and the granite, they may be called e x t e r i o r m a r g i n a l i n t r u s i o n s, leaving the name i n t e r i o r m a r g i n a l i n t r u s i o n s for those in the granite.

Epidioritisation.

The great majority of the gabbroid rocks mentioned above, both those of the interior marginal intrusions as those of the exterior marginal intrusions, are more or less completely recrystallised, amphibolitised and converted into a type of rock, for which the name epidiorite is accepted.

The different stages of recrystallisation of these gabbroid rocks are so well represented in this area that the process of epidioritisation can be perfectly followed up in all its stages from the study of a series of slides. A comparison of the chemical composition of an unaltered typical gabbro (see analysis of the gabbro on Anna's Rust on page 42) with that of the entirely epidioritised rock (see analysis of the epidiorite on Rietpoort on page 45) proves that the gabbroid rock during epidioritisation is not chemically altered but only recrystallised. There is no essential difference in composition between the unaffected gabbroid rock and the perfect epidiorite. The original unaffected rocks are gabbro, olivine-gabbro, hyperite, norite and locally some pyroxenite.

The commonest type of the gabbroid rocks in the Vredefort area was originally without doubt a hyperite, carrying more or less rhombic pyroxene as larger crystals only, and gradually passing into a gabbro, through the amount of rhombic pyroxene becoming reduced.

Initial stage. In the process of epidioritisation of this commonest type the initial stage is thus represented by unaltered gabbro chiefly consisting of augite (diallage) and a basic plagioclase allied to labradorite; further a certain amount of rhombic pyroxene in larger crystals only and ilmenite in varying proportions. As a rule some micropegmatite is present as the last product of crystallisation.

First stage of epidioritisation. The crystals of rhombic pyroxene and to a lesser degree those of diallage are replaced by slender and fibrous crystals of an actinolitic amphibole. Otherwise the rock is still unaltered.

Second stage. The rhombic pyroxene has disappeared. The monoclinic pyroxene is partly replaced by a mosaic (often a more or less thread-like aggregate) of actinolitic amphibole, which is quite fresh. A portion of the pyroxene-substance remains unaltered and the outlines of the crystals of pyroxene are little or not disturbed. Slender crystals of actinolite begin to grow out from the partly recrystallised pyroxenes chiefly in the direction of the vertical axes of the latter. In this stage the plagioclase, although in places somewhat affected by the growth of the slender prisms of actinolite, remains unaltered, and the same holds good for the ilmenite. Neither titanite nor zoisite are found as yet.

This stage of amphibolitisation is found in the gabbro of the dykes on Vleispruit and on Smalfontein.

Third stage. The pyroxenes, although not quite annihilated yet, are almost entirely replaced by a vigorous growth of actinolite-prisms which now become more massive. The original form of the crystals of pyroxene has largely disappeared. The plagioclases are in many places attacked by the crystals of actinolite which grow out from the centres of activity i.e. the former now nearly vanished crystals of pyroxene. Ilmenite begins to be resorbed and at its cost titanite appears. Zoisite makes its appearance as a rule first at the border of prisms of actinolite, where those are in contact with laths of plagioclase, and also in and between the laths of felspar. Ophitic structure is still well preserved, and the same holds good for the micropegmatite.

Fourth stage. The pyroxene has entirely disappeared and its place is taken by an aggregate of massive but elongated prismatic crystals of actinolite (Pl. VIII, fig. 2 and 3). A mosaic or irregular mat of these crystals fills almost the entire slide. The ophitic structure is still visible from the arrangement of the felspar-laths. These are much attacked and disturbed by the vigorous growth of the actinolite-crystals which penetrate into them from different directions. Their bulk is diminished and zoisite now partly replaces them. The composition of the remaining felspar appears not to be altered, and the angles of extinction point to a labradorite. The ilmenite is entirely or almost entirely replaced by titanite, some remnants or kernels of unaltered ilmenite still being visible in many instances within the crystals of titanite. Much zoisite, often of a somewhat honeycombed or spongy texture, is present. In places the ophitic structure indicated by the arrangement of the laths of felspar has vanished and been replaced by a kind of mortar-structure, in which twins of albite or an allied acid plagioclase make their appearance.

Fifth stage. This stage resembles much the fourth, but a great portion of the plagioclase has now been replaced by zoisite and the ophitic structure is much obscured, and replaced largely by a kind of granular or mortar-structure. In this granular groundmass quartz is discernable but albite plays the prominent part. Even in this stage some of the larger original crystals of basic plagioclase have escaped destruction. The original micropegmatite has completely disappeared.

Sixth stage. The entire rock consists of an actinolitic amphibole, zoisite and more or less titanite. The rock is a zoisite-amphibolite. This is an extreme instance of recrystallisation, which the authors only found realised in one single rock forming part of a marginal gabbroid intrusion on Witbank. [1])

Although the name epidiorite is generally accepted to denote gabbroid rocks in which the pyroxene has suffered alteration into amphibole, it is clear from the description given above that the replacement of ilmenite by

1) The stages given above are not meant to denote the sequence of the successive phases of alteration in every rock, but only to enumerate all the stages observed in the area, arranged in increasing order of recrystallisation ; thus the initial stage indicates the unaltered original rock and the fifth phase the most advanced stage of alteration observed, the sixth phase representing an exceptional local case only.

titanite, the forming of zoisite leading to a partial or sometimes total replacement of the basic felspar by zoisite and some albite, and in the most advanced stages the destruction of the ophitic structure and its replacement by a kind of mortar-structure containing albite [1]) are phenomena just as characteristic for the entire process of epidioritisation as the conversion of the augite into hornblende. Thus the definition of the name epidiorite, if applied to the rocks of the Vredefort area ought to be somewhat modified and to read as follows :

Epidiorite is a gabbroid rock in which the pyroxene has been replaced by amphibole, the ilmenite by titanite and the basic felspar partly or entirely by zoisite, amphibole and albite, the ophitic structure being replaced finally by a granular or mortar-structure in which albite plays the role of newly formed mineral. The most conspicuous feature, however, is the amphibolitisation of the pyroxenes.

The chemistry of the process of epidioritisation can in its main points be explained as follows:

The composition of the original gabbro is : augite $(Mg.Fe)Ca(SiO_3)_2$ often with some enstatite $MgSiO_3$, labradorite $CaAl_2Si_2O_8 + NaAlSi_3O_8$ in the proportion (1—3): 1, and ilmenite $FeTiO_3$.

The augite (and the enstatite) are now replaced by actinolite (uralite) $(Mg.Fe)_3Ca(SiO_3)_4$. For this recrystallisation there is not enough Mg and Fe available in the monoclinic pyroxene ; Mg is taken from the enstatite and Fe from the ilmenite. Then there remains a surplus of Ca and some SiO_2. These combine with the rest of the destroyed ilmenite to form sphene $CaSiTiO_5$ and also help to form zoisite $Ca_2(AlOH)Al_2(SiO_4)_3$. The Ca of the destroyed basic plagioclase enters into the composition of the zoisite and its Na helps to form the albite, which is only found in the more advanced stages of recrystallisation.

Causes of epidioritisation. It is generally admitted that the process of epidioritisation is caused or at least largely promoted by pressure. Dynamic action as the chief agent in the metamorphism leading to the origin of epidiorite is accepted by such authorities as WILLIAMS [2]) for the greenstone-schist areas of the Memominee and Marquette regions of Michigan and by J. HORNE and J. J. H. TEALL [3]) for the diabase-dykes in the Lewisian Gneiss of the Highlands of Scotland. It is true that under the microscope the individual minerals of the epidiorite do not show much signs of pressure, but WILLIAMS (p. 206) has given an explanation of this fact. The actinolitic hornblende, and also the zoisite, are secondary products in the rock, results of metamorphism, and thus it is not strange that one rarely sees in them the effects of that mechanical action which caused the metamorphism. Macroscopically both in the Michigan area and the

1) Compare G. H. WILLIAMS, **92**, p. 207.
2) G. H. WILLIAMS, **92**.
3) B. N. PEACH, J. HORNE a. o., **64**.

Scottish Highlands the effects of dynamic action are much in evidence; in fact in both these regions the original igneous rocks have been converted into more or less schistose rocks, often hornblende-schists. In the Vredefort-area there is in the epidiorites macroscopically little evidence of terrestrial stresses. A schistose structure is neither developed nor indicated in the great majority of the epidiorites of the Vredefort area, which behave in the field like unaltered rocks. Microscopically they often appear strained, micro-crushzones being frequently developed.

The authors believe that also in the Vredefort area pressure probably combined with a long-lasting high temperature, has been the main cause of the epidioritisation of the marginal basic intrusions of the Vredefort granite for the following reasons:

1. At the time that the marginal gabbroid rocks were uptruded, the rocks in which we see them now injected were buried under a heavy load of sediments, comprising the bulk of the sedimentary rocks of the Witwatersrand System and the entire complex of rocks of the Transvaal System. Thus these igneous rocks during and after their period of consolidation have been exposed to great general pressure, comparable to a kind of hydrostatic pressure exerting a tremendous force but not leading to such movement as would result in the development of schistosity.

2. All the rocks of the district and in the first place the Vredefort Granite itself reveal under the microscope the effects of powerful pressure by their being crushed in many places and locally being mylonitised. The crushing, however, is not accompanied by movements except at certain spots and on a small scale, and schistose structures of any extent or importance are not developed in connection with this crushing.

3. There is a great variation in the extent to which epidioritisation of the gabbroid rocks has taken place and it is difficult to explain why such a pressure as postulated above should leave a gabbro in one place unaltered and convert another close by into epidiorite.

The authors cannot offer a complete explanation of this, but they wish to point out, that also in other respects the effects of pressure are unevenly distributed in the entire area concerned. Mylonites and flinty crush-rocks are found in one spot and not in another; lines of quartz-mosaic are seen cutting across the minerals in a slide of one granite while nothing of this is found in a section of another granite from a spot close by. Crush-zones are found in all rocks older than those of the Karroo System [1]) throughout the entire area, but erratic in one portion and not in another.

Thus the internal effects of pressure are, as a matter of observation, strong but unevenly distributed all over the area. The authors find that this also holds true of epidioritisation. An exact explanation cannot be given as yet but the results of pressure are, at any rate, consistent with one another

1) With the exception of the enstatite-granophyre.

as regards their irregular distribution, no matter what particular effect or what particular class of rocks is concerned.

Are these gabbroid intrusions in the Lower Witwatersrand Beds just outside the periphery of the granite, the exterior intrusions, related to the intrusions of the same class of rock close by in the granite near its periphery, the interior intrusions?

The answer to this important question may be approached through several lines of reasoning.

a. The Argument from Petrographical Similarities. The striking similarity in mineralogical composition and microscopic habit, the practical identity of the various stages of conversion of pyroxene into amphibole, referred to above, give strong support to the surmise that both types of basic intrusions are closely connected as derivations of the same parent magma and as manifestation of the same period of igneous activity.

b. The Argument from Chemical Composition. Three bulk analyses are given below ; two of these (I and II) are of typical epidiorite-sills, the third (III) is of the gabbro of Anna's Rust (quoted above) and is repeated for comparison :

	I.	II.	III.
SiO_2	51.65	52.5	51.7
TiO_2	.95	1.15	1.35
Al_2O_3	14.6	10.5	14.4
Fe_2O_3	.3	4.5	3.3
FeO	11.1	9.65	9.5
CaO	9.85	10.95	9.75
MgO	6.95	7.25	7.6
Na_2O	2.65	2.30	2.15
K_2O	.65	.20	.55
P_2O_5	.10	.10	nil
H_2O (110° C.)	.25	.20	.20
Loss on ignition	1.0	.06	.05
	100.05	99.90	100.55
Sp. Gr.	2.96	2.95	2.98

1. Epidiorite from Tweefontein, partly epidioritised gabbro (exterior basic intrusion in the Lower Witwatersrand Beds). Analysis by H. G. WEALL, Government Laboratories, Johannesburg.

II. Epidiorite from Rietpoort, wholly epidioritised gabbro (exterior basic intrusion in the Lower Witwatersrand Beds). Analysis by ditto.

III. Gabbroidal Sill, Anna's Rust, non-epidioritised gabbro (interior basic intrusion in granite). Analysis by ditto.

A comparison of these analyses at once reveals a close similarity in chemical characters. This similarity is so striking that it can scarcely be purely accidental, specially in view of other points of petrographical resemblance, which were pointed out above. The authors, in consequence, find it very difficult to resist the conclusion of a community in origin of exterior and interior intrusions.

c. *The Argument from Field Relationships round the Tweefontein Boss.* At only one place does the field-evidence afford a clear indication of relationships, viz. on Tweefontein, where a sill in the ferruginous Water Tower Slates cuts like a dyke right across one of the intrusions at the periphery of the granite (fig. 7) which at this place has invaded the lowermost strata of the Witwatersrand Beds. Having accepted that the marginal intrusions in the granite are related to and about synchronous with the updoming of the granite and the accompanying overtilting of the girdle of sediments, the sill-like intrusions in the Lower Witwatersrand Beds can *a fortiori* not be older than these phenomena.

The Tweefontein case showing a sill in the Witwatersrand Beds to be younger than a marginal boss in the granite, may be one example of small local divergencies or overlapping in relative age and is not adverse to our opinion, that as a whole the two groups of intrusives are closely related both in composition and in age ; this is not surprising in view of the probability that the igneous activity extended over a considerable length of time.

d. *The Argument from the transverse Faults.* Throughout the Vredefort Mountain Land there are numerous transverse faults breaking across the Lower Witwatersrand Beds. Although these are undoubtedly later in age than the emplacement of the basic intrusions (whether external or internal), the fact that such faults affect *both* types of intrusions makes it unlikely that one is dealing with two periods of intrusion, genetically independent and of totally different ages.

Further, the fact that the faults, which are the result of stresses, consequent upon updoming and overtilting, have displaced both types of basic intrusions, does not at all necessarily imply, that the latter existed long prior to, and are genetically independent of, the updoming. It is probable, indeed, that both the faults and the intrusions denote one kind of relief from the stresses set up by the Updoming of the Vredefort Granite. Hence, so far from the displacement of the intrusions by later faults denoting genetic independence of two sets of phenomena, it is highly probable that these are closely connected as the result of a definite chapter in the magmatic history discussed below in Chapter VI.

In this connection the girdle of sediments which surrounds the Bushveld Plutonic Complex in the Central Transvaal affords some highly instructive analogies. It is well known that this girdle is broken across by faults [1]) in a manner essentially similar to that observed in the Lower Witwatersrand Beds round the Vredefort Granite. These dislocations are likewise due to the stresses set up by the emplacement of the Norite magma of the Bushveld Plutonic Complex. The faults also displace a series of basic intrusions

1) For details the reader may consult A. L. HALL, **25** and **26**, and G. A. F. MOLENGRAAFF, **60**.

(including epidioritised gabbroidal rocks) lying within the surrounding Pretoria Series and corresponding to the exterior intrusions of the Vredefort Mountain Land. They likewise affect portions of the basic margin of the Bushveld — corresponding to the interior marginal intrusions within the Vredefort Granite. These phenomena can be studied at Pretoria and south of Haenertsburg in the N.-E. Transvaal and provide a very striking analogy to the course of events which make up the geological history of the Vredefort Mountain Land.

e. The Argument based on Volume and Distribution. Whatever may have been the exact mechanism of the basic intrusions, it is clear that the peripheral contact-zone between the Vredefort Granite and its encircling sediments is the most favourable belt over which intrusive phenomena would occur, because that belt represents a zone of weakness owing to differences in behaviour between granite on the one hand, and sediments on the other, under the stresses and volume changes resulting from updoming, expansion, subsequent contraction etc. On these *a priori* grounds one would anticipate the maximum display of basic intrusions — as regards both volume and number — along and on both sides of (but near to) the main contact. This is exactly what the distribution indicates. The interior intrusions are confined to the periphery of the granite and the exterior ones are most marked along the main contact in the sediments nearest to the granite; as one passes into higher horizons they diminish in number and volume, become much reduced in the upper portion of the Lower Witwatersrand and are almost wanting in the Upper Witwatersrand Beds.

An exact counterpart to this kind of distribution is seen in the Pretoria Series round the periphery of the Bushveld e.g. at Pretoria and between Belfast and Lydenburg.

f. The Argument based on variable complexity of the Intrusions. On the view of a genetic connection between the exterior and interior group of basic intrusions one would anticipate finding now and then some marked differences in the degree of complexity, which the form of the intruded bodies would assume. This follows from the fact that the exterior group invades a series of sediments made up of more pliable argillaceous rocks and highly resistant quartzites. Among such a group of rocks the intrusions would tend to follow the more yielding shaly bands in between the resistant quartzites and hence appear as sills. Yet remembering that the intrusions were emplaced under the influence of tremendous forces associated with the overtilting, the magma would no doubt break here and there across the strata in highly irregular fashion. The interior intrusions, on the other hand, occurred within a large mass of granite which — from the present point of view — may be regarded as a single tectonic unit free from major directional properties. If, as the writers believe, the granite acted as a kind of buffer, the mechanism would result in a system of more or less horizontal potential (not actual) fissures corresponding in principle to a kind tectonic exfoliation *(‚tektonische Aufblätterung')*. On such *a priori* grounds one would expect to find the interior intrusions simple in form and constituting horizontal or slightly inclined sills, with occasional more or less vertical feeding channels.

The above anticipations are realised in the field with this exception only that locally the interior intrusions have over comparitively short distances invaded the lowermost portion of the encircling belt of sediments (the Tweefontein boss-like intrusion). Reference has already been made to the highly complex nature of the big epidiorite sill on Tweefontein (fig. 8) shown on PENNY's map. Other and essentially similar cases occur on Brakfontein, in the central and western portion of Rietpoort etc. where large fragments of sediments behave as if floating about in epidiorite. Definite evidence of the sill-form of interior intrusions exists e.g. on Anna's Rust, and of a vertical feeding channel e.g. on Witbank. This evidence has been given above on pp. 31 and 32.

In this case also, the Bushveld Plutonic Complex supplies a striking analogy in various intrusive transgressions e.g. N.-W. of Lydenburg, or near Dullstroom, where the exterior intrusions break across and engulf the sediments of the Pretoria Series.

The lines of reasoning given above have led the authors to favour the view of a close genetic relationship between exterior and interior basic intrusions.

Against the opinion advocated here might be brought forward an alternative, assuming that the sills of epidiorite are intruded in the Witwatersrand Beds independent of and prior to the updoming of the Vredefort boss. This alternative would appear to be supported by the fact that the occurrence of gabbroid intrusions as sills in the lowermost beds of the Witwatersrand is not restricted to the Vredefort area only. In fact a sill of diabase with an average thickness of 76 m. [1]) is found in the central portion of the Witwatersrand north of Johannesburg intruded in a corresponding horizon viz. in the shales which there are intercalated between the two main groups of quartzite-bands belonging to the Orange Grove Quartzites. On closer inspection, however, there appears to be no reason to give to this apparent analogy much weight. The latter intrusion, the age of which is unknown, is confined to a portion of the Witwatersrand only; in the environs of Heidelberg, which are mapped in detail by ROGERS [2]), it is not observed. Moreover, in the Witwatersrand the intrusion keeps always its position in the same horizon of shales and cuts neither through the overlying nor across the underlying bar of quartzite, and thus behaves in a manner quite different from that of the sill-like intrusion in the Lower Witwatersrand Beds in the Vredefort area. Considering, moreover, that this alternative assumption would fail to explain the obvious similarity between the exterior and interior intrusives in the Vredefort area, the authors think that the first opinion given is by far to be preferred.

1) E. T. MELLOR, **54**, p. 124..
2) A. W. ROGERS, **71**.

c. *Dykes of Enstatite Granophyre.*

At the periphery of the Vredefort granite-boss another system of dykes is developed, which is younger than any of the intrusions mentioned above. These dykes run more or less parallel to the periphery of the granite. They stand vertical or nearly so. Their width is variable but on the average they are massive dykes, a width of over 30 m. not being rare.

From west to east the authors first encountered this system of dykes on Driehoek, a portion of the former large farm Rietkuil 554, where near the homestead of Rensburg a dyke of this enstatite-granophyre cuts one of the marginal dykes of gabbroid rocks, consisting here of a partly uralitised hyperite, which at this place crops out in a well-marked hill. From this spot the dyke of enstatite-granophyre has been followed towards south-west over some distance, where its cuts through the granite. Its further continuation westwards or south-westwards is unknown as yet. From Rietkuil towards the north-east and later east this system of dykes is well developed along the periphery of the granite (Plates XXXVI, XXXVII and XXXVIII). The farthest point east where one of the authors has observed such dykes is on the farms Zijferfontein and Vergenoeg, south of the Vaal River, where enstatite-granophyre is found near the edge of the granite, cutting the Orange Grove Quartzites. They have not seen such dykes at the south-eastern and southern margin of the Vredefort Granite, and it must be left to a later detailed survey to decide whether they occur there or not.

As can be easily read from the coloured map and the sketch-maps on Plates 36—38 these vertical dykes cut across the granite and all the surrounding sediments, also across all the marginal intrusions of gabbroid rocks and their derivatives, the epidiorites. They are equally posterior to all the crustal disturbances which took place in connection with the updoming of the periphery of the granite and consequently they always cut the uptilted sediments rather obliquely, the direction of their outcrops making a small angle with the line of strike of the strata. In cutting the different formations they have destroyed the weaker and shattered the more resisting ones. Numerous fragments of the invaded rocks remain in the form of xenoliths in the dykes but a good deal of them has, as it appears, been assimilated by the injected rock. This fact is reflected in the mineralogical and chemical composition of the latter.

In the field the rock of these dykes is seen in most places to be crowded with xenoliths of the particular kind of material through which it has forced its way and the number of these xenoliths is often large enough to convert the dyke-rock into a pseudo-igneous breccia in the composition of which the xenoliths may perhaps represent more than 50 per cent. One of the finest examples of such breccias is found on Rietpoort, west of the main road, where the enstatite-granophyre has broken through and shattered the lowermost bars of the Orange Grove Quartzites (Pl. IV

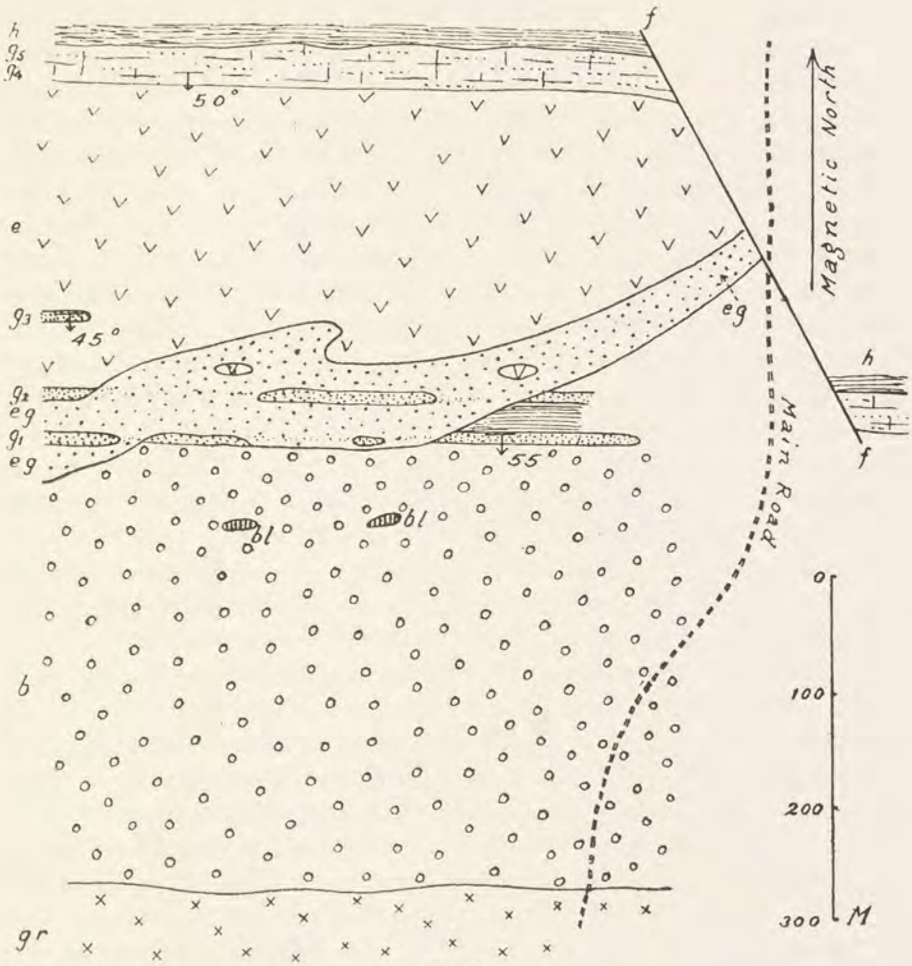

Fig. 9.

The intrusions near the edge of the Vredefort Granite on Rietpoort. *gr.* Vredefort Granite, *b.* Basal Amygdaloid, g_1—g_5. Orange Grove Quartzites, *h.* hornfels, *e.* epidiorite, *e.g.* enstatite-granophyre, *bl.* blocks of hornfels in Basal Amygdaloid, *f.* fault.

fig. 1 and 2, Pl. IX fig. 1 and fig. 9). Numerous angular blocks of quartzite ranging from the size of a mans head downwards are found here suspended in a matrix made of enstatite-granophyre. By their white colour they contrast vividly with the matrix and protrude from it (Pl. IX, fig. 2) by their greater resistance to weathering. In many places these pseudo-igneous breccias are polygenous and carry blocks of rocks which do not occur in the near vicinity, which proves that the xenoliths may have been transported by the molten rock over a good distance. Thus e.g. on Witbank, where the enstatite-granophyre cuts as a powerful dyke with a width of 48 m. through the kopje of granite just behind the school, xenoliths of granite are rare, but those of quartzite plentiful. The latter can only have been derived from the Orange Grove Quartzites which crop out at the margin of the granite at a distance of some 450 m. and must have been cut in depth. This is understandable taking into account that the dip of the Orange Grove Quartzites here is 70° towards the granite (probably by underthrusting). Xenoliths of recognisable granite are always rare, even where the enstatite-granophyre over a good distance cuts through granite-country only, because they are partly assimilated by the dyke-magma or else altered beyond recognition.

It is a fine sight, when standing on the Baviaanskrans at the boundary of the farms Kopjeskraal and Koedoeslaagte, to see the dyke on Witbank coming from the granite to cut obliquely across the Orange Grove Quartzites on kopje A (see map) as well as across the hornfels on top of these, and then to make for a conspicuous kopje of granite behind the school. The dyke cuts right across this kopje, being visible even from that distance, as a somewhat depressed streak; it then cuts through a marginal dyke of gabbroid rock, crosses the Vaal River, whence it can be followed in the hills for a good distance through the granite, until it bifurcates and the main branch turns more eastward towards the homestead on Rietpoort (Pl. XXXVII and XXXVIII). It crosses on its way several transverse faults without being affected in the least in its course, this proving that the faults are older than the dyke and that the walls of the former must have been well cemented together again when this intrusion took place.

The mineralogical composition of the dykes is, apart from differences in number and character of the enclosed xenoliths, rather constant and so is their appearance in the field. Their outcrops do not show agglomerates of rounded boulders like the majority of the gabbroid intrusive rocks show, but as a rule a fairly smooth surface on which loose often somewhat angular boulders lie scattered. The colour of the rock is grey and the weathered skin is thin. Where these dykes cut through the Basal Amygdaloid, the differences between the two rocks are easily overlooked in the outcrops, but on closer inspection the weathered surface of the enstatite-granophyre can always be distinguished by its greyish colour from that of the Basal Amygdaloid which has a reddish-brown tint.

The enstatite-granophyre is a fine-grained, almost dense rock; with a pocket-lens not much can be made out regarding its constituent minerals. Under the microscope the rock proves to be made of rhombic pyroxene, probably enstatite, in small somewhat plump prisms bounded by the two pinacoids {100} and {010}, monoclinic pyroxene, which often forms the outer zone of the rhombic crystals, rather basic plagioclase in lath-shaped crystals, usually simply twinned after the albite-law, a good number of flakes of brown strongly pleochroic biotite and some grains of ore in rows of small octahedral skeleton-crystals, all these elements being surrounded by abundant granophyre.

In one locality only, on Rietkuil, where the enstatite-granophyre cuts hyperite as a powerful dyke and has been quarried for the building of a school near by, some amphibole is found as a primary constituent in the rock in small sharply defined prisms bounded by the faces of the prism {110} slightly truncated by the pinacoid {010}. The amphibole is green and strongly pleochroic a palegreen, b olivegreen, c dark bluish-green; by this pleochroism and by its higher angle of extinction it is will distinguished from actinolite.

The micropegmatite-structures distinctly start from the crystals of plagioclase (Pl. X, fig. 1) and often, especially in the marginal portion of a dyke, form large units (Pl. X, fig. 2) with simultaneous extinction, which then may surround and enclose several individuals of pyroxene and plagioclase giving the rock under the microscope a coarse-granular and poikilitic appearance. The laths of plagioclase, from which a granophyre-unit starts its growth, always show a rim which is more acid than the kernel. Such a rim grows out as the felspathic component of the granophyric intergrowth or eutectic, as is shown by the extinction of this component being simultaneous with that of the rim of the felspar. The growths of granophyre in the rock are most vigorous, where xenoliths of quartzite are most abundant; the granophyre, however, is never missing, not even in those portions of the rock which are free from xenoliths. The granophyre is in places thread-like, resembling myrmekite.

As a rule the mineralogical composition and the texture of the rock do not show any differences near the xenoliths; in a few instances only a faint rim is found around the xenoliths caused by a moderate concentration of minute prisms of enstatite apparently growing out from the margin of the xenolith.

The xenoliths, the great majority of which are either of quartzite or granite, are on the contrary strongly affected. Those of quartzite show a complicated mosaic structure; the original grains which vary in coarseness all are converted into a mosaic of smaller grains as if they had been crushed. Small crystals or crystallites as well as minute flakes of biotite occur scattered in the quartz-mosaic, which must have been introduced from the igneous rock. Besides, the granophyre of the rock penetrates deeply into the xenoliths, and at their margins can be well seen to be injected into and between the quartz-grains. In fact the smaller xenoliths are freely permeated with thread-like microgranophyric elements as minute offshoots of the granophyre in the rock (Pl. X, fig. 3). Not rarely the quartz-mosaic of such xenoliths gets much finer towards their borders and then appears to merge imperceptibly into the granophyric groundmass of the igneous rock. Some xenoliths have the appearance of having been partially melted and then are torn out in streaks which gradually disappear in the groundmass of the igneous rock. All this proves that the quartzite-xenoliths are strongly attacked and doubtless to a certain extent have been assimilated by the invading rock.

The xenoliths of granite, when thoroughly altered, are no more recognisable as such. They have a crushed appearance and show a composite mosaic of felspar and quartz-grains, made of groups of small grains which are united together into larger more or less rounded individuals which are cemented by a finer-grained mosaic. Transitional stages between little altered fragments of granite and such thoroughly altered xenoliths reveal, that the crystals of felspar get altered each into a somewhat rounded individual or large grain composed of a mosaic of small grains of felspar and quartz, that the original quartz of the granite gives rise to the cementing mosaic of small quartz-grains and that the biotite is converted into patches of an opaque dull brownish substance, which in later stages of alteration disappears gradually. Finally, these altered xenoliths of granite are injected with granophyre of the dyke-rock just as well and in the same way as those of quartzite.

Along its contacts with the different rocks through which it cuts enstatite-granophyre shows, well developed selvages; macroscopically these are dark, compact and heavy rocks with a vitreous lustre. Under the microscope the rocks of these selvages afford beautiful examples of rapidly cooled rocks with about the same composition, as shown by examination of specimens taken from five widespread localities, viz. Rietkuil, contact with hyperite; Witbank, contact with granite; Kopjeskraal, contact with granite; Rietpoort, contact with quartzite and granite; Zijferfontein, contact with quartzite. In these selvages the only mineral found in the slides in well developed crystals is a rhombic pyroxene. It is distinctly pleochroic, $\mathfrak{a}$ pale yellowish-brown, $\mathfrak{b}$ pale reddish-brown, $\mathfrak{c}$ pale bluish, and may be hypersthene. It forms slender prisms bounded in the well-defined prism-zone by the two pinacoids (100) and (010), sometimes slightly truncated by the prism (110). The prisms show no terminal faces but grow out in linear series of sometimes transversely broken crystallites. The rest of the rock consists of an imperfect crystallised groundmass in which minute flakes of biotite, crystallites of rhombic pyroxene and abundant very small black specks, probably of magnetite, can be detected. The groundmass shows a beautiful spherulitic structure. The spherulites are seldom round but generally elongated and then often have the shape of sheaves, the slender crystals being developed prevailingly in two opposite directions. The longest diameter of such spherulites can attain 3 min.; when many of the spherulites have such a large size, the vitreous lustre of the rock shows undulating shades on rotation. In each of these sheaf-like spherulites the crystals — probably of felspar — are often parallel and thread-like over good distances; these thread-like crystals show a low angle of extinction. In some instances the largest diameter and some of the principal radii of a spherulite are denoted by the position of slender crystals of a rhombic pyroxene, which, where the spherulites are more spherical, may be arranged like the spokes of a wheel.

In most cases, however, a thick somewhat radiating bunch of delicate crystallites or rods of rhombic pyroxene appears to form the centre of each spherulite, rendering this centre more or less opaque by their high index of refraction. In comparing slides of specimens of the selvage with those, taken further away from the contact with the country-rock, it appears, that the spherulites must be regarded as micro-crystalline varieties of the somewhat vermicular granophyre-units found in the more central portions of the dyke. The ore, probably magnetite, is to a considerable extent concentrated in the selvage, where the rock is perfectly crowded with minute, black specks. Monoclinic pyroxene is entirely absent in the selvage, suggesting that at first rhombic pyroxene alone is precipitated from the melt and that only in a somewhat later stage of crystallisation monoclinic pyroxene begins to develop and appears gradually to replace the rhombic pyroxene.

The effects of the igneous rock on the xenoliths in the selvage are much the same as in the more central portions of the rock described before. In some instances the spherulites appear to have a microscopic xenolith as nucleus from which they grew out. Glass was not observed but may however have been present; it cannot be made out how much of the cryptocrystalline portion of the rock may be due to devitrification of a former glass-base.

The *chemical composition* of the enstatite-granophyre dykes is shown by the following three analyses:

Analyses of Enstatite-Granophyre.

	I.	II.	III.
SiO_2	67.4	63.7	67.45
TiO_2	.4	.5	.4
Al_2O_3	12.5	12.75	12.2
Fe_2O_3	.65	1.0	.9
FeO	6.5	7.6	6.15
MnO	.15	.1	.15
CaO	4.5	5.8	4.4
MgO	3.9	4.2	4.1
K_2O	1.85	1.8	2.0
Na_2O	1.6	2.4	1.7
CO_2	.05	.05	.05
P_2O_5	.3	.2	.1
Moisture (110°C.)	.1	.2	.1
Ignition loss	nil	.1	.2
Total	99.90	100.40	99.90
Sp. Gr.	2.7	2.8	2.79

I. Enstatite-granophyre from Rietpoort just west of neck on road to Potchefstroom, Analysis by H. G. WEALL, Government Laboratories, Johannesburg.

II. ditto, from Kopjeskraal near boundary with Rietpoort, free from visible xenoliths. Analysis by H. G. WEALL.

III. ditto, from Rietkuil free from visible xenoliths. Analysis by H. G. WEALL.

The dykes from which the analysed samples I and III are taken cut through granite; the dyke from which sample II is taken cuts at that spot both granite and Basal Amygdaloid.

On the farm Kopjeskraal quite near the boundary of Rietpoort, where the big dyke of enstatite-granophyre, an analysis of which is given in the second column of the table on page 60, cuts through granite and Basal Amygdaloid, it sends out a narrow apophysis into the granite (Map and Fig. 10). This apophysis begins with a thickness of about 4 m. and can be followed over

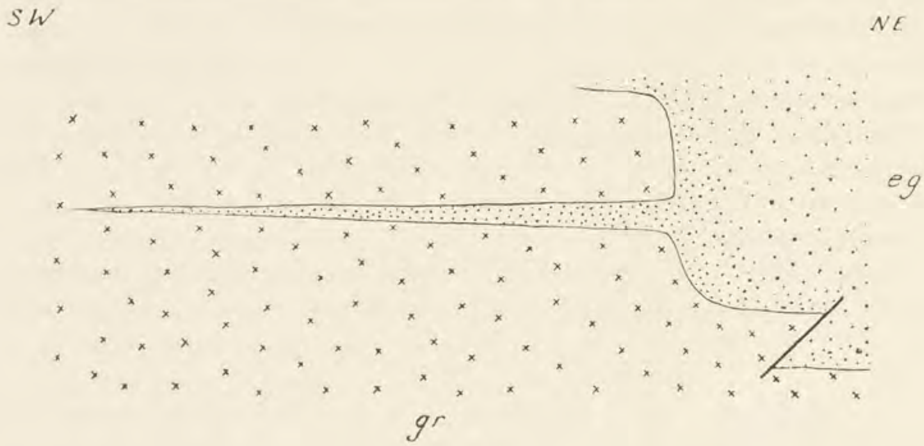

Fig. 10.

Apophysis or tongue of enstatite-granophyre in granite on Kopjeskraal. *gr.* Vredefort Granite, *eg.* enstatite-granophyre. Selvage densily dotted.

a distance of about 100 m. into the granite; it thins out gradually, dwindles down to a width of less than one centimetre, and finally appears to run out into a joint-plane in the granite. In this apophysis spherulitic structure (Pl. X, fig. 4) is extremely well developed; the spherulites consist of bunches of enstatite-needles apparently imbedded in a granophyric substance. Where the thickness of the apophysis has diminished to 5 cm. or less, the rock becomes more and more opaque under the microscope, small black specks, probably of magnetite, increasing rapidly in numbers. Even when the rock finally becomes almost opaque and the spherulites get small and difficult to distinguish, small phenocrysts of a rhombic pyroxene are still recognisable.

The rock of this apophysis, especially of the thinner portion near its apex, shows a great similarity to some spherulitic varieties of flinty crush-rock, such as e.g. are found on Zijferfontein where veins of that rock cut across granite. Enstatite, which is one of the most characteristic minerals of the enstatite-granophyre, however, has not yet been observed so far in any of the flinty crush-rocks of the Vredefort area.

d. *Bosses of Alkali Granite and their accompanying Dykes of Nepheline Syenite.*

Alkali Granites.

In the girdle of tilted and overtilted sediments which encircle the Vredefort granite-boss four bosses of alkali-granite (coloured map, and Fig. 11 and 12) were intruded during or more probably shortly after their tilting. One of these is situated in the central and upper portions of the Lower Witwatersrand Series on the farms Schurvedraai, Witbank and Koedoeslaagte, another close by on the farms Schurvedraai and Koedoeslaagte following more or less closely the boundary between the upper and lower portions of the Witwatersrand System, and one again in a much higher horizon, in the Dolomite on the farms Rietfontein 555 and Rietfontein 664. A fourth very small boss is found in the Lower Witwatersrand Series on the common boundary of the farms Koedoesfontein and Buffelsfontein, which is not indicated on the map.

They are all composed of medium- to fine-grained arfvedsonite-aegyrine-biotite-granite and show a great uniformity and a marked petrographical family-likeness. In specimens there is just enough difference to enable one to distinguish the rocks of any one boss from those of the others with certainty. In contradistinction to the much older Vredefort Granite the alkali-granites nowhere show a streaky or a gneissic structure, nor rapid alterations in grain. All of them are cut by dykes of nepheline-syenite which from the bosses penetrate for some distance into the surrounding sediments.

The alkali-granites of these bosses are light-coloured rather salic rocks containing a fair amount of visible quartz, and this general character is reflected in the following analyses made by Mr. H. G. WEALL, Government Laboratories, Johannesburg.

Analyses of Alkali Granites.

	Percentage figures I	Molecular ratios Ia	Percentage figures II	Molecular ratios IIa	Percentage figures III	Molecular ratios IIIa
SiO_2 . . .	74.35	1.2425	67.3	1.1278	70.65	1.1815
TiO_2 . . .	0.15	.0019	0.5	.0006	0.3	.0004
ZrO_2 . . .	—	—	0.10	.0008	0.05	.0004
Al_2O_3 . . .	13.35	.1312	16.65	.1641	15.25	.1500
Fe_2O_3 . . .	1.35	.0084	2.5	.0157	1.7	.0107
FeO . . .	1.1	.0153	1.75	.0244	1.65	.0231
MnO . . .	0.05	.0007	trace	—	trace	—
CaO . . .	0.85	.0152	0.95	.0171	0.85	.0152
MgO . . .	0.45	.0112	0.75	.0187	0.5	.0125
Na_2O . . .	5.1	.0824	6.2	.1005	5.2	.0842
K_2O . . .	2.9	.0310	2.6	.0278	3.5	.0372
P_2O_5 . . .	0.1	.0007	0.15	.0011	nil	—
CO_2 . . .	nil		nil		nil	
H_2O at 110° .	0.15		0.3		0.2	
H_2O, loss on ignition .	0.3		0.4		0.35	
	100.20		100.15		100.20	
Sp. Gr.	2.62		2.63		2.63	

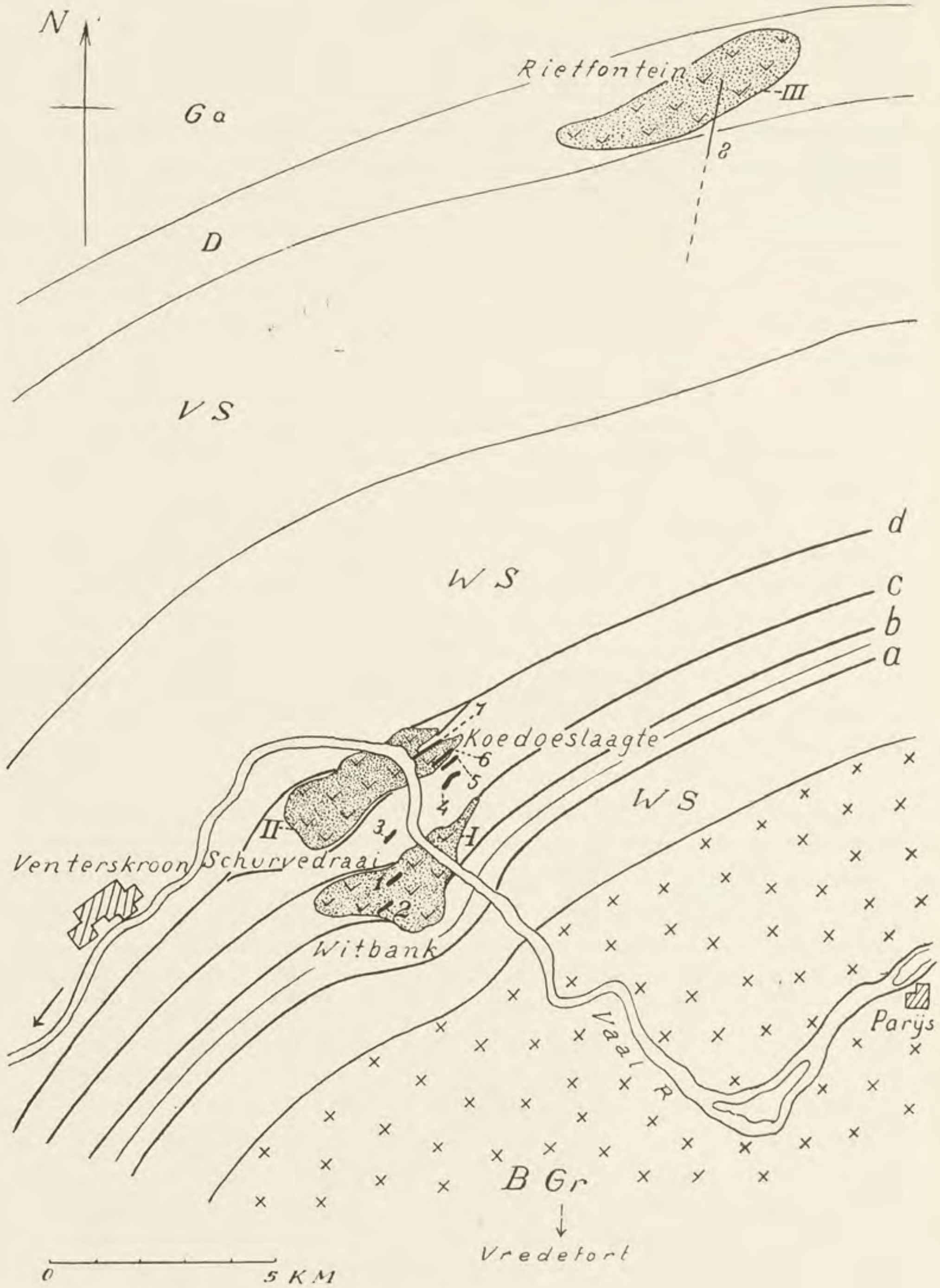

Fig. 11.

Sketch showing the position of the stock-like laccolithic intrusions in the Vredefort Mountain Land. *BGr*. Biotite Granite, *WS*. Witwatersrand System, *a*. Hospital Hill Quartzites, *b* and *c*. Government Reef Quartzites, *d*. Main-Bird Reef Quartzites, *VS*. Ventersdorp System, *D*. Dolomite, *Ga*. Gatsrand Beds, *I*, *II* and *III*. Bosses or stock-like laccolithic intrusions of Alkali Granite, *1—8*. Dykes of Nepheline Syenite.

I. Arfvedsonite-soda-granite. Centre of boss 1, Witbank. Analyst H. G. WEALL, Government Laboratories, Johannesburg. Probably a hybrid, acidified rock.

II. Arfvedsonite-soda-granite, boss 2, Koedoeslaagte. Analyst H. G. WEALL, Government Laboratories, Johannesburg.

III. Soda-granite, boss on Rietfontein. Analyst H. G. WEALL, Government Laboratories, Johannesburg.

During its intrusion the magma of these bosses made room for itself,

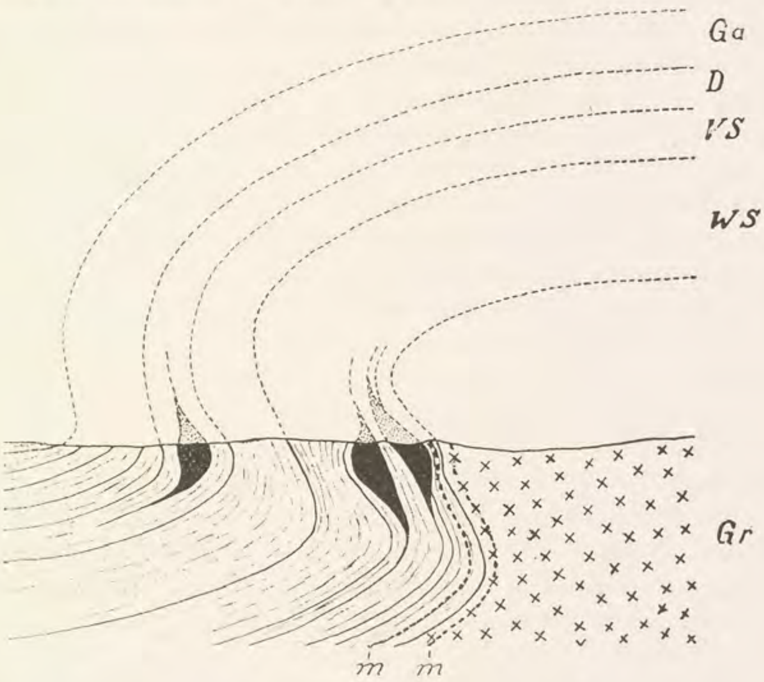

Fig. 12.

Ideal section showing the position of the bosses or stock-like laccoliths (black) in the belt of sediments round the Vredefort Granite. *m*. Main horizons of basic marginal intrusions, *Gr*. Vredefort Granite, *WS*, Witwatersrand System, *VS*. Ventersdorp System, *D*. Dolomite, *Ga*. Gatsrand Beds.

partly by pushing aside the hard surrounding layers i.e. the quartzite-bars of the sedimentary complex (Fig. 11 and 12), partly by assimilating material from the sediments. Contact-metamorphism is well developed around the bosses. It is excellently marked where the alkali-granite is intruded outside the belt of highly thermally altered sediments which encloses the Vredefort Granite, as on Rietfontein, but much less distinguishable as such, where the bosses of alkali-granite lie within that belt. In the latter case as for example on Witbank and Koedoeslaagte, it appears that the alkali-granite has intensified existing effects of thermal metamorphism in the sediments.

a. The first boss, on Schurvedraai, Witbank and Koedoeslaagte (I in Fig. 11).

Seen from the road from Parijs to Vredefort this boss lies in a westerly direction just behind the powerful ridge of the Hospital Hill Quartzites known as the Baviaanskrans, beyond the spot, where in the Baviaanspoort this ridge is traversed by the Vaal River. It occurs at a distance of only two and three quarters of a km. from the edge of the Vredefort granite-mass.

The boss is about three and a half km. long and one km. broad and crossed, about midway along its shortest diameter, by the Vaal River. It lies low compared with the enclosing ridges of quartzite and the area occupied by the granite of this boss forms a rolling plain, which south-west of the river is nowhere higher than about 20 m. above the level of the Vaal River. North-east of it in the Transvaal side the boss forms smooth rounded hummocks which in altitude do not surpass a level of 40 m. above the river. Along the river good outcrops of rock are not found but some distance away from it, where the vegetation is scanty, the undulating surface offers many fine and extensive outcrops. It is not easy, however, to obtain perfectly fresh specimens, because the rock is somewhat weathered, and quarries are not made in this boss nor, as far as the authors know, in any of the other masses of alkali-granite.

The colour of the rock is determined by the somewhat pinkish hue of the felspar; femic minerals are not much in evidence and are evenly distributed.

Excepting along selvages the grain of this alkali-granite remains much the same all through the boss.

There is some difference in composition between the rock exposed north of the river in the Transvaal and that exposed south of it in the Orange Free-State. North of the river the alkali-granite is much decomposed, fairly rich in biotite and relatively poor in arfvedsonite; south of the river it is much fresher and arfvedsonite is the ruling femic mineral.

The mechanical effect on the surrounding sediments of the emplacement of this boss is remarkable and can best be studied from the behaviour of the resistant quartzites.

The powerful bar of the Hospital Hill or Green Quartzites of the Baviaanskrans has been thrust against the Vredefort Granite, and consequently its general line of trend, which is everywhere else concave with respect to the latter granite-mass, here has been converted into a straight and locally even slightly convex line (Map and Pl. XXXVII). Near the Vaal River on Koedoeslaagte close to its right bank this quartzite bar is broken by a transverse fault and displaced over a distance of fully 300 m. by which movement the Lower Hospital Hill Quartzite on the right bank of the river is brought in line with the Upper or Main Hospital Hill Quartzite on the left bank (Pl. XI, fig. 1).

At the south-western end of the boss of alkali-granite the main quartzite-bar shows a twist and from there further south-west and south resumes its normal trend parallel to and concave towards the circumference of the Vredefort Granite. It is not unlikely that the conspicuous minor faults on Witbank (Pl. XI, fig. 1 and Pl. XXXVII), which have affected only the strata stratigraphically underlying the Green Quartzite, are caused by the same pressure originating from the uptruding of the alkali-granite.

The stratigraphically next higher bars of quartzite (*b* and *c* in Fig. 11) which are the equivalents of the Lower Government or Coronation Quartzites at the Witwatersrand, are on both sides of the river clean cut off against the boss of alkali-granite. On Witbank, where the authors have more closely examined the abutting of the quartzite-ridge *b* against the granite, they found that the strata of the quartzite can be followed for a small distance in a more or less shattered condition into the boss of alkali-granite but soon lose their coherence and disappear as a rapidly fading trail of blocks in the granite. The granite itself shows at the contact a hyperacid selvage; it has taken up many xenoliths which appear on its surface as numerous small protruding blebs of quartz and quartzite; in fact the granite has been converted at the contact into a very acid hybrid rock.

The magma of this boss has been acidified throughout by the assimilation of all this quartzitic material, as shown by the high figure for silica in an analysis by H. G. WEALL, Government Laboratories, Johannesburg of an average sample of fresh rock from the centre of the boss (column I of Table on page 74).

This boss of alkali-granite has been intruded in that portion of the belt or aureole of sediments around the Vredefort Granite, which is altered by thermal metamorphism. It is, however, intruded in a horizon of this belt, where the metamorphism is less strong than nearer to the Vredefort Granite. Comparing the rocks close to the boss of alkali-granite with those in the same horizon some distance away outside its altering influence, it becomes obvious that the metamorphism has been intensified by the influence of the alkali-granite. In fact the sediments close to the latter show the highest degree of thermal metamorphism, such as some distance away is only found much closer to the Vredefort Granite, e.g. in the horizon of the Hospital Hill or Green Quartzites, and from there stratigraphically downwards.

A certain type of hornfels containing much staurolite is confined to the contact-aureole around this boss and has not been found by the authors anywhere else in the belt of metamorphosed rocks.

β. The second boss on Schurvedraai and Koedoeslaagte.

At a distance of about one and a half km. to the north-west of the first boss a second boss of alkali-granite is intruded in the Witwatersrand Beds, in a higher horizon, viz. in the Main-Bird Reef Series (Pl. XII and Pl. XXXIX).

It has a similar shape and is about as large as the above mentioned first boss, being five and a half km. long and one to one and a half km. broad. It is also crossed about midway along its shortest diameter by the Vaal River just above the bend of the river on Schurvedraai, whence that stream flows for about eight km. in a south-westerly direction within the great slate-body in the Upper Witwatersrand Beds, known as the Kimberley Slates. This granite-boss has a low elevation above the riverbed, with the exception of a portion of its south-eastern margin on Schurvedraai which extends to about half the height of the northern slope of the ridge of Bird Reef Quartzite, and of a portion of its northern margin on Koedoeslaagte which equally creeps up the southern slope of the same quartzite to approximately 40 m. above the river. Fairly good outcrops are found scattered both on Schurvedraai and Koedoeslaagte. On Koedoeslaagte at a spot where a road happened to be in repair high on the right bank of the river, just where the alkali-granite had invaded a ridge of the Upper Quartzites of the Bird Reef Series, very good specimens could be obtained.

There is some difference in the composition of the alkali-granite between the south-eastern and the north-western portion of this boss. In the south-eastern portion the alkali-granite is medium-grained somewhat coarser than the average rock of the first boss. It has a white colour and is dotted over with irregular black specks. These specks are larger than those in the rock of the first boss and amphibole can easily be distinguished in them as the chief constituent. In the north-western portion the alkali-granite is also medium-grained, but instead of being pink, like that of the first boss, it has a grey colour with a tinge of violet. Besides by its colour the rock is easily distinguished from that of the south-eastern portion by its higher content of biotite so that the good-sized flakes give it the appearance of being slightly less salic. The emplacement of this second boss has led to a very complicated structure, as shown by the irregular distribution of the Bird Reef Quartzite and the Jeppestown Slate, which always directly underlie it (stratigraphically). The detailed mapping by Mr. L. T. NEL indicates that the structure is essentially that of a faulted anticline ; on Schurvedraai runs a low curved feature of higher ground along the northern edge of the boss, composed of the Bird Reef Quartzite with its associated Jeppestown Slates, but rapidly wedging out towards the east and vanishing as the Vaal River is approached (Pl. XXXIX). On the south side of the boss the same quartzite-slate band is seen, so that at first sight it looks as if the magma had made room for itself by splitting, and wedging itself in between two bars of quartzite. But the dip in the northern curved arm is to the north, while in the lower one it is to the south, and since across each feature the succession is complete, the emplacement of the magma gave rise to an anticlinal structure. The latter was accompanied by faulting, and a displaced section of the quartzite-slate-band has moved so as to make a short feature running from south to north. On the eastern side of the Vaal River, on Koedoeslaagte, the ridge of the Bird Reef Quartzite has remained in its normal position, followed on the south by the Jeppestown Slates in their proper order ; the northern curved branch of these rocks cannot in fact be regarded as the direct (attenuated or assimilated) continuation of the ridge defining the northern edge of the boss on Koedoeslaagte. This continuation should more likely be looked for in the quartzite-slate-band forming the southern edge of the boss on Schurvedraai.

The effects of contact-metamorphism are not striking around this boss ;

this can be explained by the fact that the shaly and slaty rocks are largely concealed by surface-deposits, whereas the quartzites which predominate largely in the portion nearest to the bosses do not lend themselves to thermal metamorphism and hence are little altered. That the contact-metamorphism has, however, been effective, is well shown by the strong alteration of an amygdaloidal rock in the immediate vicinity of the alkali-granite on Koedoeslaagte. This amygdaloidal rock occurs as a contemporaneous sheet in the upper portion of the Main-Bird Series. It is typical of the Bird Reef Series not only here but also at other localities where the Witwatersrand Beds are developed, as e.g. in the vicinity of Heidelberg and again at the Witwatersrand. In the north-western portion of the flat ground on Schurvedraai are several low features surrounded by this alkali-granite ; these consist of disturbed masses of dark hornfels and quartzite, representing large xenoliths of shales probably belonging to the Jeppestown Series.

γ. *The third boss on the two farms Rietfontein 555 and Rietfontein 664.* (Map, and III in fig. 11).

This mass of alkali-granite occurs much further away at a distance of 14 km. from the periphery of the Vredefort Granite. It is intruded into and entirely surrounded by rocks belonging to the upper portion of the Dolomite Series, which is the middle division of the Transvaal System. This portion of the Dolomite Series is composed of alternating thin strata of dolomite and chert, between which in its uppermost section also layers of cherty conglomerate and brecciated chert are intercalated.

In the horizon where the intrusion has taken place, the strata either stand vertical or are slightly overtilted, so as to dip at a high angle (70°—80°) towards the south, i.e. towards the Vredefort Granite.

Just as the two other bosses, this one is elongated in the direction of the strike of the invaded sediments. Its length is six km. and its breadth one and a half km. Its outcrop thus occupies an area slightly larger than that of any of the other bosses. The presence of this intrusion is not recognisable in the landscape by any surface-indications and it appears that on the average the granite is eroded and carried away just as rapidly as the surrounding altered sediments. By far the greater portion of the boss is hidden from view by grass-covered surface-soil and good outcrops are not frequent. Signs of a pushing aside of the sedimentary beds could not be observed owing to bad exposures but it is likely to have occurred, since assimilation of dolomite on anything like a scale proportional to the volume of the intrusive magma is negatived by the analysis (see p. 63) ; the latter, moreover, agrees closely with that of the granite of the second boss on Koedoeslaagte where there can be no question of such assimilation. The unsatifactory exposure of the Rietfontein boss unfortunately prohibited a detailed study of its mode of emplacement.

The alkali-granite has a beautiful warm pink colour, much deeper than that of the first boss ; femic minerals are not much in evidence ; quartz is present in about the same or perhaps in a little larger quantity than in the rocks of the other bosses, and the grains of quartz possess more definite outlines. The rock is medium- and even-grained and resembles more a quartz-syenite than a granite, the felspars chiefly controlling its macroscopic appearance.

Contact-metamorphism is very well developed around this boss, the dolomite being marmorized or converted into peculiar felty aggregates mainly composed of tremolite.

δ. *Petrographical characters of the Alkali Granites.*

In handspecimens the alkali-granites of the Vredefort area are less trachytic than is the case with the majority of the alkali-granites of other localities, specially with those of Scandinavia. It is only in the alkali-granite of the boss on the farms Rietfontein that the felspar-crystals by their shape and arrangement more or less determine the general habit of the rock, but even here not to such a degree as is the case in some Scandinavian types. The alkali-granites of the two remaining bosses in the Witbank area, especially when somewhat weathered, have the appearance of ordinary granites and this holds good specially for the alkali-granite of the second boss on Schurvedraai and Koedoeslaagte, which is fairly rich in evenly distributed biotite and is not miarolitic to any marked extent. The alkali-granite of the first boss on Witbank and Koedoeslaagte in this respect stands in the middle between the two others because it is poorer, or at least on macroscopical examination appears poorer in coloured femic constituents, and because it has in a fresh condition a somewhat trachytoid structure.

Alkali-granite of the first boss (Map and I in Fig. 11). The bulk of the rock consists of felspars and quartz. Microcline is the predominating felspar, generally showing lamellae after the two twinning laws; where these are wanting or not seen it is scarcely possible to distinguish the microcline from orthoclase, which may also be present in moderate proportions. According to the molecular ratios given in the columns Ia, IIa and IIIa of Table I on page 63 the proportion between the molecules Na_2O and K_2O in the analysed rocks is respectively 8.2 : 3.1, 10.0 : 2.8 and 8.4 : 3.7. These proportions prove that the microcline present in the rocks must be rich in soda, and the same holds good for the orthoclase, so far as this mineral is present.

Next to microcline albite is much in evidence; it forms both larger crystals with many twin-lamellae and also aggregates of smaller crystals which as a rule only show a small number of twin-lamellae or are simple twins. Parallel intergrowths of microcline and albite of different types are frequent: in the most common type the albite is found as a microperthitic intergrowth within the microcline; less often the latter forms microperthitic intergrowths in albite. Not seldom the albite is found in well defined individuals in larger crystals of microcline; sometimes again the microcline is found in patches intergrown in larger crystals of albite. In several of the slides crystals of microcline or of microcline-microperthite are surrounded by a rim of albite and sometimes sinuous offshoots of the latter can be seen penetrating from the rim into the kernels of microcline. In other cases such kernels of microcline or microcline-microperthite are more or less cut up by a system of nearly parallel narrow streaks of albite. Quartz is present both in larger grains filling the interspaces left between the crystals of the other minerals, and as smaller grains which form aggregates together with small crystals of albite and microcline.

The femic minerals are all clustered together and thus appear macroscopically as dark specks fairly wide apart. Each cluster is composed mainly of arfvedsonite and aegirine together with ore in small grains and biotite in much varying quantities. Titanite occurs in all and zircon in the majority of the slides, confined to these clusters ; apatite occurs only here and these as long slender prisms.

Arfvedsonite takes the dominant place amongst the femic minerals. It occurs in the form of elongated prisms which show distinct faces of the prism {110}, whereas in the direction of the vertical axis they are not well terminated. At both ends of this axis the crystals often run out into thin needles. Separate small sheaf-like clusters of needles and also separate needles of arfvedsonite are found scattered in small quantities and are not seldom enclosed in the felspars.

The arfvedsonite shows the familiar strong dispersion of the bisectrices very well and is characterized by its pleochroism :

𝔞 — grey,
𝔟 — deep greyish-blue,
𝔠 — deep blue.

Examined in ordinary light the different sections offer an exquisite variety of tints, bright lavender-blue being most conspicuous under such conditions.

Amongst the femic minerals aegirine takes the second place ; it occurs in grains of about the same size as those of the arfvedsonite, rarely showing well defined crystal-outlines. Seen in ordinary light the aegirine in certain sections is very conspicuous by its bright emerald green colour. In polarized light the strong pleochroism is as follows :

𝔞 — yellow to greenish-yellow,
𝔟 — bright green,
𝔠 — deep green.

Arfvedsonite and aegirine are often intergrown in the ordinary way, with the vertical axes and the orthopinacoidal planes parallel. These intergrowths are not seldom very intricate, a veritable mosaic being visible especially in sections parallel to the plane of symmetry.

Biotite is always present but as a rule only in small quantities. The crystals show very strong pleochroism : for rays swinging parallel to the cleavage dark olive-green to opaque and for rays swinging at right angles to the cleavage golden-yellow. The biotite although it forms part of the clusters of coloured minerals, does not enter into any regular intergrowth with the amphibole or the pyroxene in this rock.

Specks of ore are rarely wanting in any of the clusters, and also titanite in quite irregularly shaped grains is frequently found wedged in between the other femic minerals.

Plump short prisms of zircon bounded by the faces (001), (100), (010) and (110) are present in varying amounts. The crystals show a most perfect zonal structure parallel to the faces of the prism (110).

The effects of the assimilation of great quantities of quartz are well visible in the mineralogical composition of the somewhat finer-grained acidified varieties of alkali-granite in the selvage of this boss at and near the contact with the lower quartzites of the Government Reef Series (compare page 67). All the slides of the rock show a great increase in the amount of the quartz, which occurs both in large and small grains, also as quartzitic aggregates; these are evidently xenoliths. The felspars of the marginal phases do not differ from those in specimens taken from the middle of the boss.

In some types of selvage-rocks taken a few feet from the contact with the quartzites epidote appears as the most prominent of the coloured minerals in good-sized grains and crystals. Under the microscope it has a pale yellowish-green colour and is clearly pleochroic. No aegirine occurs and arfvedsonite is very scantily represented, whereas biotite is present in larger quantities than in samples taken nearer the centre of the boss.

Alkali-granite, arfvedsonite-soda-granite, of the second boss (Map and II in fig. 11), *on Koedoeslaagte and Schurvedraai.* The south-eastern portion of this boss is composed of a medium-grained rock, macroscopically an unmistakable amphibole-granite in which felspars are the predominating minerals and quartz and amphibole are macroscopically well recognisable. The last mineral appears as evenly distributed black specks, which vividly contrast with the white colour of the rest of the rock.

On microscopical examination this granite differs only in minor points from that of the first boss on Witbank. Amongst the femic minerals arfvedsonite much predominates in good-sized crystals. Besides the cleavage after (110) a parting parallel to (001) is well developed and twins after the orthopinacoid are common. Besides arfvedsonite another almost identical amphibole is present in small quantities in well-defined prisms, which shows a pleochroism : $\mathfrak{a}$: dark bluish-green, $\mathfrak{b}$: deep indigo to opaque, $\mathfrak{c}$: light yellowish-green. This amphibole is probably riebeckite. Biotite is very scarce with a pleochroism citron-yellow to deep-brown, in small flakes which generally are included in the arfvedsonite. Aegirine is little represented, intergrown in arfvedsonite. Sphene is found here and there in irregular grains. The felspar consists mainly of albite and of intergrowths of microcline and albite; sometimes microcline-microperthite is found rimmed by albite.

The north-western portion of this boss is composed of a rock which on microscopical examination is seen to differ more than that of the south-eastern portion from the alkali-granite of the first boss. The general character is the same, but the rock is richer in biotite and somewhat poorer in aegirine and arfvedsonite. The femic minerals are clustered together as in the granite of the first boss, but parallel intergrowths of biotite and arfvedsonite are very common, the basal plane of the biotite being parallel to the orthopinacoid of the amphibole. The greater portion of the arfvedsonite is intergrown with and included in the larger flakes of biotite and the same holds good for the aegirine. Consequently in handspecimens biotite appears to be well-nigh the only femic mineral, whereas under the microscope each flake of biotite is seen to hold enclosed a certain proportion of amphiboles and pyroxenes.

The arfvedsonite, where it is found intergrown with biotite and aegirine, appears to have crystallized before the bulk of the felspars and then it only holds enclosed such minerals as sphene, zircon and apatite; it is also found, however, as completely allotiomorphic crystals poikilitically embracing in their wide mesh-works besides other minerals also much felspars and quartz. Obviously in the latter instance arfvedsonite was the last mineral to crystallize. It is rather interesting that in the granite of this boss calcite [1]) occurs in the majority of the clusters of femic minerals, and is in some of them the predominating mineral, where it forms aggregates of a few good-sized grains. Outside of the clusters only occasional small specks of calcite are seen in the rock, where they form part of aggregates, mainly composed of felspar and quartz. The very fresh condition of the specimens examined makes it doubtful, whether the calcite could be due to infiltration and the way in which the calcite is clustered together with the other minerals of early consolidation suggests a primary constituent.

Alkali-granite (soda-granite) of the third boss on Rietfontein. The microscopic character of the alkali-granite of this boss shows certain features distinct from those of the rocks making up the other bosses. It is a soda-granite.

The main constituents are felspar, quartz, amphibole and biotite. Besides these zircon and ore are always present, and pyroxene and titanite are observed here and there.

The felspars form the bulk of the rock. Most of their crystals are somewhat tabular parallel to (010) and are twinned after the Carlsbad-law and these twins by their arrangement determine the character of the rock, by which it is individualized from the alkali-granites of the other bosses. Each of the components of the Carlsbad-twins consist of parallel intergrowths of orthoclase, microcline, microcline-microperthite and albite, which show a great variability. The rims of the crystals often consist of albite. The components of the Carlsbad-twins as a rule meet along an irregular composition-plane.

The femic minerals are clustered together. The amphibole is idiomorphic and well crystallized, the crystals being often well terminated not only in

1) The mineral is taken to be calcite but no attempt has been made to discriminate it from other carbonates such as dolomite or magnesite.

the zone of the prisms but also in the direction of the vertical axis. The main crystalform is a somewhat stout prism. Besides the prismatic cleavage a parting parallel to (001) is well marked. Twins after the orthopinacoid are of common occurrence. The pleochroism is strong :

$\mathfrak{a}$ — light yellowish-green,
$\mathfrak{b}$ — deep olive-green,
$\mathfrak{c}$ — deep olive-green with a shade of blue.

The amphibole belongs to a type between common hornblende and arfvedsonite. Biotite and ore are common inclosures in this amphibole. Pyroxene is wanting in many of the slides and in others appears to represent a type between aegirine and diopside.

The biotite, which occurs in good-sized flakes, is a strongly pleochroic lepidomelane. The colours shown for rays swinging at right angles to the cleagave are golden-yellow to brownish-yellow, and for those swinging parallel to the cleavage, deep-brown to opaque ; smaller flakes of biotite are frequently enclosed in the amphibole and these sometimes form parallel intergrowths with their host. Ore, probably magnetite, as black specks is found scattered in the rock and also enclosed both in the crystals of biotite and of amphibole.

Zircon here and there joins the clusters of femic minerals and so does sphene. Quartz which is much in evidence fills the interspaces between the other minerals in the rock.

The chemical composition of the alkali-granites of the Vredefort Mountain Land (I, II and III) and also of some allied rocks, is shown in the following table.

TABLE.

	I	II	III	IV	V	VI	VII
SiO_2	74.35	67.3	70.65	70.59	71.24	71.65	70.40
TiO_2	0.15	0.5	0.3	0.44	0.68	trace	0.13
ZrO_2		0.10	0.05				1.65
Al_2O_3 . . .	13.35	16.65	15.25	12.38	13.78	13.04	7.85
Fe_2O_3. . . .	1.35	2.5	1.7	1.61	1.30	2.79	6.85
FeO	1.1	1.75	1.65	3.33	2.83	1.80	2.98
MnO	0.05	trace	trace	0.08	0.15		0.13
CaO	0.85	0.95	0.85	0.93	0.38	trace	0.26
MgO	0.45	0.75	0.5	nil	trace	trace	0.52
Na_2O	5.1	6.2	5.2	6.95	5.32	6.30	4.05
K_2O	2.9	2.6	3.5	3.74	5.10	3.98	2.45
P_2O_5	0.1	0.15	nil	trace			
CO_2	nil	nil	nil				
H_2O at 110°	0.15	0.3	0.2	0.21		1.10	
H_2O, loss on ignition . .	0.3	0.4	0.35	0.20			0.25
	100.20	100.15	100.20	100.46	100.78	100.66	99.65
Sp. Gr.	2.62	2.63	2.63				

I. Arfvedsonite-soda-granite, centre of boss I on Witbank. Analyst H. G. WEALL, Government Laboratories, Johannesburg. Probably a hybrid, acidified rock.

II. Arfvedsonite-soda-granite, boss II on Koedoeslaagte. Analyst H. G. WEALL, Government Laboratories, Johannesburg.

III. Soda-granite, boss III on Rietfontein. Analyst H. G. WEALL, Government Laboratories, Johannesburg.

IV. Arfvedsonite-soda-granite, Ilimausak, South Greenland. Analyst C. WINTHER.

V. Soda-granite, Iviangusat, Kangerdluarsuk. South-Greenland. Analyst C. DETLEFSEN. A hybrid acidified rock.

VI. Arfvedsonite-soda-granite, Hougnatten, Longendal, Norway. Analyst L. SCHMELCK.

VII. Arfvedsonite-granite, Ampasibitika, Madagascar. Analyst M. F. PISANI.

The analysed rocks all represent types in which amphibole is the dominating femic mineral. They are soda-granites, soda occurring in excess over potash. Iron is present in small quantities only and magnesia and lime in very small quantities.

Such leucocratic soda-granites are uncommon rocks. They have a similarity to the soda-granites described by BRÖGGER [1]) which occur intimately connected with the Nordmarkites in the Christiania area [1]). They are further related to the arfvedsonite-granite of Ilimausak (IV in table) and the soda-granite of Iviangusat (V in table) both described by USSING [2]), and the soda-granite of Hougnatten (VI in table), described by BRÖGGER [3]). The arfvedsonite-granite of Ampasibitika in Madagascar (VII in table) described by LACROIX [4]) is much richer in iron than the soda-granites of the Vredefort area.

The abundance of microcline among the felspars approaches these rocks also to the riebeckite-soda-granite of San Peter's Dome, Colorado, described by LACROIX [5]).

Nepheline Syenites.

Dykes of nepheline-syenite occur in intimate connection with the bosses of alkali-granite described in the previous pages (Geological map and fig. 11).

The dykes of nepheline-syenite either cut through the bosses of alkali-granite, from where they may extend into the surrounding sedimentary

1) W. C. BRÖGGER, **9** pp. 65—70.
2) N. V. USSING, **90** p. 114.
3) W. C. BRÖGGER, **10** p. 127.
4) A. LACROIX, **51** p. 82.
5) A. LACROIX, **50** p. 39.

strata, as in the case with the dykes 1 and 2 in the first boss on Witbank, the dykes 6 and 7 in the second boss on Koedoeslaagte and the dyke 8 in the boss on Rietfontein, or they may occur in the immediate vicinity of those bosses, as is the case with the dyke between the bosses I and II both on Witbank (3 in fig. 11) and on Koedoeslaagte (4 and 5 in fig. 11). The dykes have a varying width not exceeding 16 m. (7 in fig. 11). They stand vertical, as far as this could be proved with certainty, and their strike corresponds on the average with the general strike of the invaded sediments. In one instance a small almost equidimensional blow of nepheline-syenite is found in the alkali-granite; this occurs on Witbank quite near the contact with the invaded quartzites (Map). The authors have not been able to follow these dykes over greater distances than indicated on the map. The dykes of nepheline-syenite though genetically connected with the bosses of alkali-granite are younger than those and must have been injected after the emplacement of the masses of alkali-granite. They are, just as well as the alkali-granites, much altered by pressure and crushed and consequently in many places converted into mylonites and ultimately in pseudo-tachylytes or flinty crush-rocks. Numerous veins composed of these latter rocks cut through the alkali-rocks in various directions; on Plate XVI in fig. 2 such a vein is shown occurring in a canadite on Koedoeslaagte (5 in fig. 11).

Just as in the alkali-granites two groups could be distinguished, on the one hand those on Witbank and adjoining farms, and on the other hand the boss on Rietfontein, so the nepheline-syenites of the Witbank area are as a group distinct from those on Rietfontein.

The dykes in the Witbank area, notwithstanding considerable variety in external appearance, all consist of Canadites (SHAND), whereas the dyke on Rietfontein must be classed amongst the Foyaites.

a. The Canadites at the Vaal River.

Although the nepheline-syenites of the different dykes on Witbank, Schurvedraai and Koedoeslaagte show in many places rapid variations in grain, structure and mineralogical composition, yet they all have a strong family-likeness. They all belong to the group of the Canadites, defined by SHAND as nepheline-syenites characterized by nepheline and albite. QUENSEL[1]) first proposed the name ,,canadite'' for such rocks, but in defining the group he emphasizes the abundance of femic minerals, whereas SHAND calls the canadites rather leucocratic rocks. In this respect the rocks of the Witbank area best correspond to the type as defined by SHAND[2]), for on the average they are decidedly leucocratic rocks.

The general characteristics given by ADAMS and BARLOW[3]) of the

1) P. QUENSEL, **67** p. 177.

2) S. J. SHAND, **86** pp. 116—118.

3) E. D. ADAMS and A. E. BARLOW, 1.

nepheline-syenites of the Haliburton and Bancroft areas on pp. 228—232 of their memoir can to a great extent be applied to the majority of the nepheline-syenites of the Witbank area. The canadites of the latter area, however, do not contain calcite and in places are free from aegirine and rich in lepidomelane, when they correspond to the litchfieldite-type, as described by BAYLEY [1]).

The canadites of the Witbank area are made up essentially of an acid plagioclase, usually albite, but also anorthoclase, nepheline, cancrinite, aegirine and biotite (lepidomelane).

Microperthite and probably also microline-microperthite are usually found intergrown with albite but seldom in appreciable quantities. Orthoclase is scarce; microcline is occasionally found but ranks merely as an accessory constituent bar in one instance, a portion of the big dyke 7 on Koedoeslaagte, where this mineral forms an essential component of the rock. Amphibole is observed in dyke 7 only.

All the varieties observed pass one into the other, generally abruptly. Although each of the dykes shows one or more characteristics of its own, by which it can be singled out, such characteristics apply more to the way in which the different varieties of the canadite-type are represented, than to the exclusive appearance of certain types in certain dykes.

The rocks are usually massive, but in many places they possess a more or less perfect banded or even foliated structure, which as is the case in dyke 6 sometimes presents a schistose development (Pl. XV, Fig. I). Massive and banded streaks may alternate repeatedly. They vary in texture from fine to coarse-grained, while in pegmatitic phases nepheline and anorthoclase occur as individuals as much as 20 cm. in diameter.

The pegmatitic phases may occur as more or less parallel streaks intercalated in smaller-grained rock, especially where the latter is more or less banded; in other places the pegmatite may occur in irregular patches, and also the rock may present a quite massive development over a good distance, which at once is interrupted by the appearance of clusters of phenocrysts of large dimensions. (Pl. XIII, fig. I.)

The contact of these pegmatites with the massive rock is generally quite sharp; sometimes there is, however, a quite perceptable transition from the pegmatite into the smaller-grained type, especially in case the rock is banded.

The Canadite-pegmatite is generally composed altogether of nepheline and anorthoclase, or of nepheline and albite, in places accompanied by large individuals of aegirine; in the Litchfieldite-type large flakes of biotite occur and aegirine is absent.

The rocks are, as a rule, quite fresh and unaltered. They possess a true hypidiomorphic granular structure. Effects of pressure are much in evidence but appear to be independent of banded or schistose structures.

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1) W. L. BAYLEY, 4.

The order of crystallisation is not quite definite. Magnetite, apatite and sphene were the first minerals to crystallise, and after those aegirine and biotite were formed; albite and allied felspars came next in order; nepheline as a rule is crystallised somewhat later than the felspars and cancrinite is the last mineral to crystallise.

Numerous exceptions, however, have been observed to this general order of crystallisation; thus nepheline may be found included in felspar, and lepidomelane may poikilitically embrace such salic minerals as albite and nepheline.

Mineralogical composition.

The following minerals enter into the composition of the nepheline-syenites of the Witbank area.

Main constituents.

Nepheline.	Aegirine.
Cancrinite.	Biotite (Lepidomelane).
Felspars.	

Accessory constituents.

Hornblende.	Apatite.
Muscovite.	Magnetite.
Sphene.	

Nepheline. The nepheline is quite fresh; under the microscope it is colourless and transparent. Macroscopically on fresh fractures of the rock it is recognisable by its greasy luster; its colour is grey to faint greenish.

In the porphyritic varieties nepheline occurs both in the groundmass and as phenocrysts. The latter have the shape of short plump prisms, bounded by the faces of the basal pinacoid and the prism $\{10\bar{1}0\}$; they may attain a diameter of about 10 cm. (dyke 4).

On the weathered surface the crystals of nepheline by their relatively rapid weathering are invariably indicated and easily discernable by pits or depressions (Pl. XIII, fig. 2 and Pl. XIV) surrounded by rims composed of minerals such as felspar or aegirine. This peculiar method of weathering has been described by BROUWER [1]) from the aegirine-foyaite of Leeuwfontein and by ADAMS and BARLOW [2]) from nepheline-syenites of the Haliburton area. The shape of these pits or depressions is either hexagonal or quadratic. The surface of the nepheline in these depressions is often shagreened and coated by a thin film of a bluish-grey (Pl. XIII, fig. 1) enamel [3]); in other cases it is even and dull greyish-blue (Pl. XIII, fig. 2 and Pl. XIV).

1) H. A. BROUWER, **11** p. 38.

2) E. D. ADAMS and A. E. BARLOW, **1** p. 236.

3) A similar coating is described by ADAMS and BARLOW, **1** p. 236.

The crystals of nepheline in the groundmass may be idiomorphic and then they often show a perfect zonal arrangement of their inclusions which as a rule chiefly consist of needles of aegirine. The figures 2 and 3 in Pl. XV represent sections of crystals of nepheline showing this zonal arrangement, which are cut respectively at right angles and parallel to the optical axis.

In other rocks the crystals of nepheline are not quite idiomorphic and well bounded by crystal-faces in the zone of the prism only, but bluntly terminated in the direction of the optical axis. As a rule such crystals have fairly large dimensions and the enclosed needles of aegirine then are arranged exclusively parallel to the main axis. Such crystals are often surrounded by a rim of larger prisms of aegirine, which do not show any special orientation. One gets the impression that the nepheline during its growth has pushed aside the larger preexisting crystals of aegirine and has crowded them together in an irregular rim at its periphery, and also that the crystallisation of the aegirine still continued during the period of growth of the crystals of nepheline. The slender needles of aegirine of this period were orientated and forced into a position parallel to the main axis of the nepheline.

In other rocks again the nepheline is perfectly allotriomorphic and is found wedged in between the crystals of felspar in a similar way as quartz in granites. In such cases the nepheline has little or no inclusions, and a specific arrangement of those which are present is wanting or deficient.

Besides aegirine all the other minerals, cancrinite excepted, may be found enclosed in nepheline, but never in abundance.

Cancrinite. This mineral, although present in notable quantities in several nepheline-syenites of the Witbank area, is erratic in its occurrence and can only be distinguished by the aid of the microscope. It occurs in irregular perfectly allotriomorphic grains of about the same size as those of albite and nepheline in the non-porphyritic portions of the rocks. It also occurs as thin beady rims surrounding crystals of felspar or nepheline and again it may enter into cracks or fissures, specially in felspars. This may explain, why it is sometimes found apparently enclosed in felspar.

Under the microscope the cancrinite is transparent and colourless, free from inclusions, quite fresh and consequently free from alteration-products. It always occurs somewhat concentrated in streaks and patches and in some of the dykes streaks are found where the mineral occurs in quantities great enough to make it one of the dominant minerals. Where this occurs the name c a n c r i n i t e - c a n a d i t e would be appropriate. An exceptional fine variety of this type (Pl. XVI, fig. 3) is found in the banded portion of the big dyke 7 on Koedoeslaagte, which is a granular rock made of grains of about equal dimensions of albite, nepheline and cancrinite without femic minerals. Albite is the preponderating mineral, next comes cancrinite and then nepheline. The latter is scarce or even absent in some portions of this rock.

This cancrinite-canadite sometimes contains as the sole femic constituent lepidomelane in such quantities that the name cancrinite-litchfieldite would be justified.

The cancrinite is a primary constituent, and even where it occurs in very small grains, arranged as beady rims bordering such minerals as nepheline and felspar it does not make the impression of a secondary element.

Felspars. The felspars form as a rule the bulk of the rocks, but locally nepheline may preponderate over felspar. Anorthoclase is the dominant, if not the only, felspar among the phenocrysts. Its crystals often attain large dimensions (Pl. XIII, fig. 1 and Pl. XIV) and diameters of about 15 cm. are not rare. Albite, and with it allied plagioclases poor in anorthite, is by far the ruling felspar in the massive portions of the rocks. Next in order of frequency comes anorthoclase. Microperthite is always present intergrown with albite but never as abundant as in the allied soda-granites. Microcline is erratic, wanting in many of the rocks and rather abundant in some of them (e.g. in the Litchfieldite-type in dyke 7).

These minerals are quite fresh and transparent ; even in specimens taken from near the surface the felspars show only a slight turbidity due to minute scales of micaceous decomposition-products.

The crystals of albite are more or less tabular after the brachypinacoid. The twin-lamellae are well developed after the albite-law ; the smaller crystals are as a rule simply twinned, the larger show repeated twinning and then the lamellae are often so close together, that they become difficult to distinguish. The anorthoclase occurs in rather large more irregular plates with either no albite-lamellation or only a very shadowy indication, or with a patchy form of extinction resembling quartz with undulatory extinction.

Orthoclase has been rarely observed with certainty and is very scarce.

Aegirine and Biotite. These are never met with in equal quantities, either one or the other dominating. In most of the occurrences aegirine is the ruling femic mineral and biotite is either rare or absent ; in some of them (the Litchfieldite-type in dyke 7) biotite is the predominating femic mineral and aegirine is either scarce or wanting. In other portions of this dyke aegirine is the dominant femic mineral.

The pyroxene occurs chiefly in the form of long and slender prisms which may take the shape of needles ; not rarely, however, the prisms are stouter and less elongated, and sometimes they are more or less tabular after the orthopinacoid. The mineral is taken to be aegirine by the authors ; as to its optical proporties, the straight extinction the position of the bisectrices and their dispersion, it conforms to typical aegirine, but the pleochroism is absent or hardly perceptible. The colour is faint yellowish-green. In some instances (dyke 7) in the kernels of the crystals the following pleochroism was observed :

$\mathfrak{a}$ — bright green to olive-green,

$\mathfrak{b}$ — light-green,

$\mathfrak{c}$ — very pale yellow,

whereas the rims of those crystals again show hardly any pleochroism. The faintness both of the colour and of the pleochroism suggests that the bulk of the pyroxene must be an aegirine with some of the iron replaced by alumina.

Biotite is rare or absent in most of the rocks though sometimes the ruling femic mineral (portion of dyke 7). This rock, the Litchfieldite-type, carries biotite in abundance both in the porphyritic portions in phenocrysts as flakes up to 14cm. in diameter and in smaller crystals scattered through the rock. The phenocrysts show on their cleavage-planes the traces of the three systems of gliding-planes well. The mineral is a lepidomelane with very strong pleochroism from straw-yellow to opaque. It not rarely poikilitically encloses crystals and grains of all the other minerals with the exception of the cancrinite. In the rocks where the biotite is subordinate it contains generally many specks of ore, and joins the crystals of aegirine.

Hornblende. This mineral is rare, found in appreciable quantities only in the dyke 6 on Koedoeslaagte as small prisms together with and in between prisms of aegirine. Its pleochroism is strong :

𝔞 — deep bluish-green to opaque,
𝔟 — dark olive-green,
𝔠 — yellowish-green.

The dispersion of the axes of the ellipsoid is great and the mineral appears to be intermediate between arfvedsonite and barkevikite.

Muscovite. Muscovite is found in fair amount in certain varieties of the Litchfieldite-type rich in cancrinite. It occurs in ill-defined flakes ; bands rich in cancrinite and free from muscovite alternate with bands in which muscovite dominates over cancrinite. The latter in these rocks is perfectly fresh and shows no signs whatever of alteration ; it is therefore possible that the muscovite is a primary constituent and not an alteration-product either of nepheline or of cancrinite.

In the other rocks some muscovite is found in small scales due to the decomposition either of nepheline or of felspar. Seen the great preponderance of soda over potash in these rocks, it is probable that the muscovite is a soda-muscovite or paragonite. The presence of this mineral in igneous rocks is not generally accepted, but it is reasonable to expect that soda-muscovite would be found as a product of alteration of soda-minerals rather than the ordinary potash-muscovite.

The muscovite is easily distinguishable from the cancrinite by its stronger relief and its higher interference-colours.

Sphene or Titanite. This mineral is on the average well represented among the accessory constituents, in microscopic crystals only. It is erratic in its occurrence, sometimes much in evidence and sometimes very scarce or absent. It is generally found in irregular grains and with aegirine ; where the latter shows a parallel and streaky arrangement of its crystals the grains of sphene lie with their longest diameter in the same direction. In some of the localities the sphene is found clustered together in patches and then the grains have a very irregular shape as if they were much corroded.

Apatite is rare and only observed in some of the dykes (locality 1), well crystallised either in slender or plump prisms.

Magnetite. This mineral is always present in specks or more frequently in well-defined microscopical crystals with triangular, quadratic or hexagonal outlines. Sometimes the crystals are scattered all through the rock, but more often they are clustered together with or enclosed in flakes of lepidomelane or aegirine. Not rarely they are crowded at the periphery of aegirine-prisms.

Zircon. This mineral is present in most rocks in a few well-defined microscopic crystals with zonal structure. The colour of the mineral is slightly yellowish; the crystals show the characteristic strong relief and the usual brillant interference colours.

Chemical Composition.

The chemical composition of two varieties of canadite from Koedoeslaagte are given in columns I and II of the following table, and those of some allied rocks are added in columns III—V.

Analyses of Nepheline Syenites.

	I	Ia	II	III	IV	V	VI
SiO_2	57.3	0.9632	56.9	48.60	51.58	60.39	57.78
TiO_2	0.3	0.0037	0.15	1.34	0.35	—	1.83
ZiO_2	nil	—	—	trace	—	—	—
Al_2O_3. . . .	22.3	0.2205	20.7	19.89	19.40	22.57	15.45
Fe_2O_3. . .	4.1	0.0258	5.0	2.97	4.26	0.42	3.06
FeO	1.1	0.0154	1.0	5.76	5.25	2.26	3.11
MnO	trace	—	—	0.36	0.20	0.08	0.98
CaO	2.75	0.0496	1.0	4.43	3.64	0.32	1.72
MgO	0.25	0.0062	0.5	1.32	0.49	0.13	1.13
Na_2O	9.1	0.1481	11.7	8.74	7.49	8.44	11.03
K_2O	1.95	0.0210	2.5	2.26	4.23	4.77	2.89
P_2O_5	nil		0.1	0.56	0.15	—	—
CO_2	nil		0.05	1.10	1.53	trace	—
H_2O at 110°	0.2		0.05	0.21	—	—	0.94
H_2O loss on ignition . .	0.45		0.4	1.73	1.02	0.57	
	99.8		100.05	99.27	99.59[1]	99.95	99.92
Sp. Gr.	2.61		2.75				

I. Coarse nepheline-syenite from Locality 7 on Koedoeslaagte. Analyst H. G. WEALL, Government Laboratories, Johannesburg.

Ia. The same rock. Molecular ratios.

II. Fine-grained nepheline-syenite from Locality 7 on Koedoeslaagte Analyst H. G. WEALL, Government Laboratories, Johannesburg.

III. Dark-coloured canadite, Byske, Almunge district, Sweden. Analyst M. DITTRICH.

1) Including SO_2 0.10; F 0.06; S 0.01; BaO 0.05; Ce_2O_3 0.59.

IV. Nepheline-syenite (canadite), Monmouth Township, Ontario, Canada. Analyst M. F. CONNOR.
V. Litchfieldite, Litchfield, Maine. Analyst L. G. EAKINS.
VI. Nepheline-syenite (arfvedsonite-canadite), Tuoljbucht, Finland. Analyst H. BERGHELL.

The great preponderance of soda over potash explains the scarcity of orthoclase and the abundance of albite. The absence of carbondioxide in the analysis I, notwithstanding the common occurrence of cancrinite in these canadites, can only be explained by the fact that this mineral is rather erratic in its occurrence. This analysis is evidently made from a fragment in which cancrinite is absent or nearly so. [1])

Comparing the analyses of these rocks with those of other localities besides the above-mentioned strong preponderance of soda over potash, the high

[1]) In a previous paper (G. A. F. MOLENGRAAFF and A. L. HALL **63**) the authors have published the following analysis of a canadite made from a sample of fine-grained variety collected from the strong dyke 7 on Koedoeslaagte,

	A Percentage figures	B Molecular ratios
SiO_2	61.65	1.0347
TiO_2	0.2	.0025
ZrO_2	nil	—
Al_2O_3	20.5	.2025
Fe_2O_3	3.5	.0221
FeO	0.7	.0099
MnO	trace	—
CaO	2.75	.0495
MgO	0.35	.0087
Na_2O	8.8	.1429
K_2O	0.85	.0091
P_2O_5	nil	—
CO_2	nil	—
H_2O at 110°	0.15	
H_2O loss on ignition	0.5	
	99.95	
Specific Gravity	2.7	

In calculating the norm of this rock from the molecular ratio given in column B it becomes evident that after having used all the alkali-molecules and the lime for the building up of felspar-molecules and all the magnesia for hypersthene, a residue of silica still remains. This means that from a magma of the composition given in this analysis A nepheline could not possibly crystallize; and yet in slides made of samples of the same locality a fair to considerable proportion of nepheline is seen to occur. The explanation of this apparent contradiction has probably to be sought in the fact that the rock is patchy and that the analysis was not made from the same sample from which the slides were cut.

In column II of the table on page 82 another analysis is given made from a sample of the same fine-grained variety of canadite found in dyke 7 on Koedoeslaagte, which shows a much lower silica-percentage. A slide made of the same sample contains much nepheline.

percentage of silica also attracts attention. These features explain the pronounced leucocratic character of the rocks.

The chemical composition has a similarity, but not a close one, to those of the canadites of Almunge [1]), and of Monmouth Township [2]) which served QUENSEL as types in distinguishing his special group of canadites. The composition of these rocks is given for comparison in columns III and IV. The chemical composition of the variety of canadite containing lepidomelane as the sole femic constituent, to which BAYLEY [3]) has given the name Litchfieldite is added in column V, because certain dark streaks in the canadite of locality 7 on Koedoeslaagte have a mineralogical composition nearly identical with that of the rock described by BAYLEY.

The rocks of Koedoeslaagte according to these analyses contain more silica, and less iron and calcium then the canadites of Almunge and Monmouth Township. One has, however, to take into account that in the case of the Almunge rock only the dark-coloured commonest type is analysed. The Almunge rock, however, shows a great diversity of types, and the dark-coloured varieties, rich in femic minerals, may grade rapidly into white or pink rocks devoid of dark minerals; these latter leucocratic varieties are not analysed. From the descriptions it appears that in the Almunge district and in Monmouth Township melanocratic rocks greatly predominate, whereas in the Witbank area by far the bulk of the nepheline-syenites is decidedly leucocratic, the melanocratic varieties being restricted to a few bands and streaks only.

Thus the nepheline-syenites of the Witbank area appear to represent one of the purest leucocratic types hitherto found, of the canadite group, i.e. of a nepheline-syenite composed chiefly of nepheline and albite. As far as can be judged from the description and the analysis the nepheline-syenite of Tuolj-bucht on the peninsula of Kola [1]) offers another excellent example of a leucocratic canadite. This rock is poorer in nepheline than the canadites of the Witbank area and contains as dark minerals arfvedsonite and some aegirine. The chemical composition is given in columm VI.

Amongst the nepheline-syenites found elsewhere in Transvaal, in the Bushveld, no canadites have been recorded.

Characteristics of the nepheline-syenites (Canadites) of the different occurrences at the Vaal River (see sketch-map fig. 11).

Locality 1. Dyke in the central portion of the soda-granite boss I on Witbank. The colour of the rock is grey with a greenish tint. It is leucocratic, and the presence of femic minerals is hardly perceptible even with the aid of a pocket-lens.

1) P. QUENSEL, **67**, p. 179.
2) F. D. ADAMS and A. E. BARLOW, **1**, p. 264.
3) W. S. BAYLEY, **4**, p. 242.
4) W. RAMSAY and V. HACKMAN, **69**, p. 139.

Under the microscope the femic minerals are represented mainly by aegirine. This occurs in abundant crystals of small size, as prisms which are much elongated after the vertical axis, but also somewhat tabular after the orthopinacoid. Twins after the orthopinacoid are not rare and a parting parallel to (001) is well marked. All the optical properties point to aegirine, but the pleochroism is absent or very faint, sometimes better marked in the kernel than in the rim. The colour of the mineral is faint greenish. The faintness both of the colouring and of the pleochroism suggests a variety in which a portion of the iron is replaced by alumina.

Biotite is rare in the massive portion of the rock but rather common in the porphyritic streaks and nests; it is a strongly pleochroic lepidomelane. Amphibole is absent. Magnetite occurs in small well-defined crystals of octahedral and dodecahedral shape. It is often clustered together with titanite, and also occurs concentrated in the flakes of biotite and at, or in, the rims of the crystals of aegirine. Zircon is found sparsely in small plump prisms terminated by faces of the pyramid. The titanite is concentrated in patches formed by irregular apparently corroded grains of curious often vermicular shapes. Some apatite occurs in small apparently corroded prisms.

The bulk of the rock consists of felspar and nepheline. Repeatedly twinned albite in semi-idiomorphic crystals is by far the predominating felspar. Some microperthite is intergrown with the albite. Anorthoclase is present in moderate quantities in crystals which in size surpass those of the albite. These crystals show a very close lamellation by minute twinning after the albite law and are also generally simply twinned after the Carlsbad law, the plane of composition between the two individuals being irregular. Microcline is rare in the massive portion of the rock, but plays an important role in the porphyritic streaks. Orthoclase is not observed.

Nepheline is abundant, semi-idiomorphic, or allotriomorphic wedged in between the crystals of felspar. It is quite fresh and thoroughly transparent, enclosing needles of aegirine in abundance. Cancrinite is erratically present in the rock in patches as good-sized quite allotriomorphic crystals.

Locality 2. Blow at the south-eastern extremity of the soda-granite-boss I, Witbank. This is a green massive medium-grained rock, which closely resembles the canadite of Locality I in the centre of the boss of soda-granite, but contains a little more sphene and some orthoclase besides albite, microperthite and microcline.

The rock is riddled by numerous more or less parallel micro-faults (Pl. XI, fig. 2) and narrow crush-zones. Along these the minerals are strained showing undulating extinctions, and somewhat shifted. In the crush-zones the individual minerals are no more recognisable and the rock is mylonitised.

Locality 3. Dyke in quartzite between the granite-bosses I and II on Schurvedraai. A massive green rock in which in places large tabular phenocrysts of anorthoclase (Pl. XIII, fig. 1) occur bounded by the pinacoids $\{001\}$ and $\{010\}$, by the hemiprisms $\{110\}$ and $\{1\bar{1}0\}$ and the hemidome

{ $\bar{1}01$ }. Some of these are twinned according to the Carlsbad law. They are up to 10 cm. long, about just as broad and up to 1 cm. thick. They are generally accompanied by large phenocrysts of nepheline in short plump prisms.

In the massive portions of the rock aegirine is the only important femic mineral. It occurs in abundant slender prisms, showing parallel arrangement, pale green colour and very faint pleochroism. Sphene and magnetite are found in small quantities ; biotite and amphibole are absent.

The most abundant felspar is albite, generally showing, together with aegirine, a parallel arrangement of its crystals. Microcline is subordinate. Nepheline occurs in more or less semi-idiomorphic crystals of uniform size and in allotriomorphic grains. Streaks rich in felspar alternate with others rich in nepheline. In the latter nepheline is by far the dominant salic mineral. All other minerals may be found enclosed in it except cancrinite, which is present in moderate quantities. The cancrinite is allotriomorphic and appears to have been the last mineral to crystallize. A system of numerous parallel cracks and micro-faults traverses the rock in one direction.

Locality 4. Dyke in hornfels and quartzite between the granite-bosses I and II on Koedoeslaagte. A massive greenish-grey rock, rich in streaks and nests which have a coarsely porphyritic or pegmatitic development. Amongst these coarse varieties some with abundant tabular phenocrysts of anorthoclase are conspicuous as well as others in which the nepheline predominates. The short stout prisms of nepheline bounded by the faces (0001) and ($10\bar{1}0$) are found in deep hexagonal or quadratic pits in the surface of the rock ; they are due to the relatively rapid weathering of the nepheline. The rims of the pits stand cut well and are composed either of felspar or of aegirine, or of both these minerals. The surface of the nepheline is shagreened and covered with a glossy bluish-grey enamel-like film. (Pl. XIII, fig. 2 and Pl. XIV).

Under the microscope the perfectly fresh massive portions show the following composition :

The chief components of the rock are albite and nepheline, and in the third place aegirine. The rock is leucocratic.

The aegirine is pale-green and very little pleochroic. It forms numerous idiomorphic crystals, all of them slender prisms and needles. Much of the aegirine is found as inclusions in the salic minerals. Ore is present in widely scattered specks generally with, or enclosed in, the scarce flakes of a biotite, which is strongly pleochroic, from dirty olive-green to opaque. Sphene is well represented as irregular grains of larger size than the prisms of aegirine with which they are always clustered.

The crystals of nepheline which occur as plump prisms are fairly idiomorphic and carry numerous inclusions, mostly needles of aegirine, which show a beautiful orientation parallel to the faces of the basal pinacoid and the unitprism. (Pl. XV, fig. 2 and 3). In some of the larger phenocrysts of nepheline aegirine is found as very long and thin needles arranged strictly parallel to the vertical axis. In such cases stouter and larger prisms of aegirine are clustered together irregularly so as to form a kind of crude rim round the nepheline.

The tabular crystals of albite are often intergrown with microperthite; moreover, needles of aegirine are in places intergrown with albite either as an exterior rim or intercalated between the twin-lamellae of the albites, when the axes *c* of the crystals of both minerals are parallel. The crystals of albite and the prisms and needles of aegirine show a well-marked parallel arrangement and curve round the more isodiametric crystals of nepheline, closely imitating the texture common in lujaurite. Cancrinite is always present in moderate quantities.

The rock is traversed by crush-zones along which the minerals are bent, broken, dislocated and in places crushed as shown in fig. 1 on Pl. XVII. In the crush-zone the rock is completely pulverized. Planes of incipient crush are indicated in the slides by lines along which minute crystals of magnetite are accumulated here and there.

This dyke has a great similarity to that of locality 3 on Witbank and possibly the outcrops observed in these two localities belong to one and the same dyke, stretching from Koedoeslaagte across the river to Witbank but lack of outcrops prevented obtaining certainty about this point. Further, at locality 4 two parallel outcrops are found; they may belong to one dyke only, and, if so, the width of the dyke of canadite at locality 4 would be not less than 35 m. It is possible, however, that in reality at this spot two parallel dykes of smaller dimensions exist.

Locality 5. Dyke in hornfels and quartzite near the edge of the boss of soda-granite on Koedoeslaagte.

The rock is a typical leucocratic canadite, composed chiefly of albite, nepheline and aegirine. Biotite, sphene and magnetite only occur in small amounts. Some crystals of aegirine in this rock show pleochroism better than is seen in any of the other canadites in this area, but others are non-pleochroic.

A parallel arrangement of the composing minerals is very little developed in this rock; the latter is traversed by crush-zones and also by veins of pseudo-tachylyte (Pl. XVI, fig. 2) which may be very minute and may dwindle down to microscopic dimensions. They will be described in the section dealing with the pseudo-tachylyte. The rock is rich in nepheline and in places somewhat porphyritic by the development of large individuals of this mineral.

Locality 6. Dyke in quartzite and soda-granite at the edge of boss II on Koedoeslaagte; a leucocratic canadite, closely resembling that of locality 5.

The rock is much strained and shows many stress-zones along which the minerals specially the albite are crushed, showing fine examples of micro-step-faulting (Pl. XVII, fig. 2). In one instance a thin vein of pseudo-tachylyte cuts the rock and is intimately connected with such a crush-zone, ending in and apparently passing into the micro-mylonite of the crush-zone (Pl. XIX, fig. 1). As will be shown below, this occurrence may help to explain the nature of the pseudo-tachylyte.

Locality 7. Dyke in soda-granite of boss II on Koedoeslaagte. This dyke is the strongest in the area and can be followed over about one mile, a longer distance than any of the others. Its width is quite distinct a short distance above the farmhouse of Mr. PRETORIUS, where it measures 16 m.

This canadite is very variable in texture; in some places it is massive, in others full of nests and streaks of pegmatite; here and there it is well banded and even schistose and in such cases either rich in aegirine or in biotite. These minerals show perfect orientation with the crystals of albite (Pl XV, fig 1). In some of the pegmatitic phases large crystals of lepidomelane, measuring up to 10 cm. in their longest diameter are much in evidence. The crystals of nepheline reach 12 cm. in length and those of anorthoclase 8 cm.

The microscopic features are no less variable than the macroscopic characters.

The principal minerals are albite, often intergrown with microperthite, anorthoclase and nepheline. Microcline is always present, sometimes in appreciable quantities. Femic minerals in most cases play a somewhat more important role than in the rocks of the other localities. Especially lepidomelane is sometimes present in considerable amount; it is strongly pleochroic, from straw-yellow to dark-green or opaque. Aegirine is usually the principal femic mineral, but may be wanting in those varieties, which belong to the Litchfieldite-type. Sometimes it is markedly pleachroic: $\mathfrak{a}$ bright green to olive green; $\mathfrak{b}$ light green, $\mathfrak{c}$ faint greenish or almost colourless; sometimes again the pleochroism is hardly perceptible. Amphibole is observed only in slender prisms together with aegirine. The former has the optical characters of arfvedsonite, but the pleochroism is exceptionally strong: $\mathfrak{a}$ indigo to opaque; $\mathfrak{b}$ dark greenish- to bluish-grey; $\mathfrak{c}$ grey to yellowish-green. Some needles remain opaque in all directions.

Sphene and magnetite occur together and are always present in small quantities. In the pegmatitic varieties slender needles of aegirine are beautifully arranged in the crystals of nepheline parallel to the faces of the prism.

In the banded and somewhat schistose varieties dark streaks or bands rich in lepidomelane (somewhat melanocratic streaks) alternate with bands entirely free from femic minerals. The rock of these melanocratic streaks in its texture and mineralogical composition closely corresponds to the elaeolite-syenite of Litchfield, for which BAYLEY [1]) has proposed the name Litchfieldite. The only dark component visible in this rock is

1) W. S. BAYLEY, 4, p. 243.

lepidomelane ; its pleochroism is bright greenish-yellow to opaque. The leucocratic streaks consist of three minerals only : albite, cancrinite and nepheline. They form a fine-grained granular rock and the dimensions of the three minerals are about equal. Albite predominates somewhat over the other two minerals but cancrinite and nepheline are either present in about the same proportion or cancrinite ranks second in abundance. The rock is perfectly fresh and most striking seen under crossed nicols (Pl. XVI, fig. 3). For this variety the name c a n c r i n i t e - c a n a d i t e would be appropriate. In this banded rock are streaks rich in muscovite (probably soda-muscovite) and free from cancrinite. The muscovite is spread in the rock in the same way as the cancrinite and may be an alteration-product of the latter.

The cancrinite is perfectly allotriomorphic in well-sized crystals or in small specks arranged into beady rims at the edges of the crystals of nepheline and albite while it also enters into cracks of the crystals of felspar.

Locally this dyke is traversed by microscopic faults and stress-zones.

β. The foyaite on Rietfontein.

The foyaite on the farms Rietfontein 555 and Rietfontein 664 occurs as a powerful dyke (8 in fig. 11) cutting through the boss of alkali-granite, described above, and the surrounding dolomite.

Its strike is *N* 28 *E* magn. and its dip about 90°. The thickness of the dyke is 28 m. It can be followed for about 2 km. from near the boundary of the farms Rietfontein 555 and Rietfontein 664 in a north-northeasterly direction to the central portion of the first farm along a series of outcrops well marked by accumulations of large rounded blocks. The dyke of foyaite on Buffelshoek is probably its southward continuation (as shown on the map) but this could not be proved, surface-soil covering all outcrops in the intervening stretch of country.

The foyaite is a pale-pink medium-grained slightly porphyritic rock. The handspecimens show pale-pink orthoclase, often white by decomposition and many irregular waxy-grey to dark-red patches of nepheline. The black minerals aegirine, aegirine-diopside and biotite are scattered freely through the rock in small irregular clusters.

Mineralogical composition.

Thin sections show the following minerals in order of abundance : orthoclase, nepheline, soda-pyroxene and biotite.

Orthoclase. This is the chief component of the rock ; some crystals are larger than the others and appear as phenocrysts. They are tabular after (010). The arrangement of the crystals is not parallel but somewhat divergent, and resembles that typical of intersertal texture. The phenocrysts are perfectly euhedral and reach a length of 15 mm. parallel to the *c*-axis, whereas the thickness of the platy crystals in the direction of the *b*-axis does not exceed 1 mm. The smaller crystals in the massive portion of the rock are euhedral, but to a lesser degree. Carlsbad twins are frequent. The crystals as a rule show a thin rim composed of albite around a kernel of orthoclase, more or less intergrown with microperthite and albite. The orthoclase is somewhat decomposed and cloudy, but the albite is quite transparent and fresh.

Nepheline. Under the microscope the nepheline is more idiomorphic than the handspecimens suggest. Although the crystals appear to be wedged in between the tabular felspars, they are often euhedral and bounded by faces of the prism and the basal pinacoid. The bulk of the nepheline is fresh and transparent, though in part turbid with the properties of elaeolite ; inclusions are few.

Pyroxene. This is represented by diopside and aegirine. The former occurs in plump prisms bounded by the faces of the two pinacoids {100} and {010} truncated by small faces of the prism {110}. The aegirine occurs in well-defined tabular crystals flattened parallel to the orthopinacoid. In the vertical zone the crystals are bounded by the faces of the orthopinacoid and the prism {110}.

Diopside shows a maximum angle of extinction with the axis *c* of 42° in sections parallel to the plane of symmetry; those of aegirine in corresponding sections have a nearly straight extinction. In the crystals of diopside the pleochroism is weak : 𝔞 yellowish-grey ; 𝔟 greenish-grey ; 𝔠 greenish to bluish-grey. In the crystals of aegirine the pleochroism is strong; 𝔞 greenish-yellow; 𝔟 emerald-green; 𝔠 dark bluish-green. The crystals of diopside often have broad rims (fig. 13) composed of aegirine, the two minerals forming together parallel intergrowths.

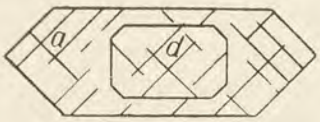

Fig. 13.
Section of crystal of pyroxene at right angles to the c-axis. *a*. aegirine, *d*, diopside.

The aegirine in the shape of its crystals and in its pleochroism resembles more closely the aegirine of the alkali-granite of the Witbank area than that of the nepheline-syenites at the same locality.

Biotite is always clustered together with the other femic constituents. It is a dark-brown variety showing pleochroism from orange-brown to opaque. A fair amount of specks of iron-ore is found in the clusters of femic minerals. Sphene was not observed and apatite only in a few slender prisms. The order of crystallisation in this rock is not well marked and the separation of all the component minerals appears to have continued up to the moment of final consolidation. The felspar is more euhedral than any of the other minerals but in places its tabular crystals are influenced in their position by pre-existing faces of crystals of nepheline.

Pyroxene is largely idiomorphic and yet laths of felspar penetrate into crystals of pyroxene and of biotite, and locally the spots where the femic minerals are clustered together then show typical ophitic texture. Biotite is in places found with good crystal-faces, but in many of the clusters it embraces poikilitically all the other minerals with take part in the composition of the rock.

Chemical composition.

The nepheline-syenite of Rietfontein belongs to the group of the foyaites. Its chemical composition is given in column I of the table below.

	I.	Ia.	II.	III.
SiO_2	55.3	0.9587	56.12	56.44
TiO_2	0.8	.0104	0.46	1.16
ZrO_2	0.15	.0013	—	—
Al_2O_3	18.25	.1858	19.62	15.54
Fe_2O_3	3.55	.0231	2.32	3.27
FeO	3.45	.0497	0.90	3.67
MnO	0.6	.0087	—	—
CaO	3.15	.0584	2.07	4.16
MgO	0.55	.0142	0.13	1.73
Na_2O	5.6	.0939	9.50	5.81
K_2O	4.65	.0514	4.17	4.27
P_2O_5	0.15	.0011	—	0.83
CO_2	Nil		0.80	0.97
H_2O, loss at 110° C.	0.6		—	0.44
H_2O, loss on ignition	3.—		3.50	2.06
	99.80		100.39	100.35
Sp. Gr.	2.58			

I. Nepheline-syenite, foyaite, Rietfontein 555.
Analyst H. G. Weall, Government Laboratories, Johannesburg.

Ia. The same rock. Molecular ratio.

II. Foyaite, normal type. Leeuwfontein 320. Transvaal.
Analyst M. F. Pisani.

III. Analcite-syenite, Mauchline, Ayrshire, Scotland.
Analyst M. Dittrich.

In columns II and III the composition of two chemically somewhat analogous nepheline-syenites is given.

According to the analysis in column I the percentage of SiO_2 in the rock of Rietfontein would in connection with the ratios of the bases hardly allow of any nepheline to be formed which is not in accordance with the observed mineralogical composition. The analysis is not made from the same specimen from which the slides were cut.

Genetic Relations between the Alkali Granites and the Nepheline Syenites.

In the Witbank area an analogy in chemical composition exists between the alkali-granite and the nepheline-syenite of the dykes, which are connected with the bosses of alkali-granite. This analogy finds its expression e.g. in the strong preponderance of soda over potash, a peculiarity which in such a marked degree is relatively rare.

The authors are inclined to conclude from this family-likeness that the alkali-granites and the nepheline-syenites are products from the same magma-hearth. The nepheline-syenite of Rietfontein shows less analogy in chemical composition with the alkali-granites and stands somewhat apart by its larger percentage of iron, which is reflected in the less leucrocratic character of the rock. Yet even here the analogy in the mode of occurrence and in other respects is great enough to warrant the surmise that the nepheline-syenites and the alkali-granites are originated from the same magma.

The authors are of opinion that the alkali-granites are later acid differentiates rich in soda derived from the same hidden magma, from which the basic marginal intrusions, described in this chapter represent earlier less differentiated phases [1]).

The nepheline-syenites probably have to be regarded as desilicated derivates of the magma of the alkali-granites.

The authors call attention to the fact that the soda-granite and the foyaite on Rietfontein have been intruded into rocks of the dolomite formation. DALY's [2]) theory on the genesis of alkaline rocks would be readily acceptable here as far as the foyaite is concerned, as soon as one admits, that the acid magma rich in soda — as stated above probably a soda-rich and acid differentiate or residue of a much larger hidden magma of more basic composition — which has been intruded into the dolomite and is now found solidified as the boss of soda-granite, absorbed in depth a certain quantity of the dolomitic rock, causing it to become locally desilicated. From these desilicated portions then originated the dykes of foyaite.

A similar explanation would appear to be untenable in the case of the nepheline-syenites on the Vaal River, because these are injected in the Witwatersrand System, of which limestones or dolomites do not form part. Yet one has to take into account, that the tilting and overtilting of the belt of sediments round the Vredefort granite-mass was accompanied by strong tectonic disturbances and dislocations. It is not quite impossible that the disturbances caused by faulting and shearing were great enough to allow masses derived from the dolomite to come in contact with and to get incorporated into the ascending magma. It certainly would be difficult to explain the presence of notable quantities of cancrinite in the nepheline-syenites on the Vaal River, in case the possibility of rocks containing carbonates being absorbed in the alkaline magma were considered to be absolutely non-existent.

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1) Compare N. L. BOWEN. The later stages of the evolution of the igneous rocks. Journ. of Geol. Suppl. to Vol. XXIII. 1915, pp. 57—59.

2) R. A. DALY, **15**. Compare also SHAND's modification of DALY's theory : S. J. SHAND, **87**.

8. Pseudo-tachylyte or flinty crush-rock.

The name Pseudo-tachylyte was applied by Shand to rocks occurring as veins in the granite at the township of Parijs, which have a great similarity to tachylyte, but cannot be regarded as true tachylyte.

The occurrence of these veins at that locality has been admirably described by Shand [1]), who, whilst admitting the great similarity between his pseudo-tachylyte and the flinty crush-rocks known from the Western Highlands of Scotland and elsewhere, also pointed out the great likeness of these veins in their mode of occurrence to true igneous veins. He came to the conclusion (p. 219) that "the pseudo-tachylyte has originated from the granite "through melting, caused not by shearing but by shock, or alternatively, "by gas-fluxing." Shand also states (p. 216) that "the form of pseudo-"tachylyte veins indicates that the granite was shattered by a gigantic "impulse or series of impulses. If this impulse were of the nature of an "explosion in the sub-crust, it would have as a necessary consequence the "outrush of incandescent gases through all the fissures of the granite. In "these circumstances fusion of the walls of the fissures might well ensue."

Shand restricted his field-observations to the near neighbourhood of Parijs, but the authors found that veins and dykes of this rock are not confined to this locality nor to the area occupied by Vredefort Granite, but that they are so numerous and wide-spread (see geological map) as to form one of the most remarkable features in the entire Vredefort Mountain Land.

In fact veins of pseudo-tachylyte were observed by the authors cutting all the sedimentary rocks older than the Karroo System. They do not know of any spot either within the granite-area or in the belt of sediments around it from the granite upwards to the Klipriver Amygdaloid where such veins do not occur. Even within the latter formation they are sometimes found. They are, moreover, seen cutting across all the intrusive rocks, dealt with in this paper in the chapter on the marginal intrusions, with the single exception of the enstatite-granophyre. Although it would be an exaggeration to pretend that no areas of any size could be found free from pseudo-tachylyte, yet the authors never failed to locate veins of this rock wherever they happened to carry out detailed research field work.

Character of the veins.

The veins are irregular in form, direction and thickness (Pl. XVIII, fig. 1 and 2). They have every inclination from vertical to horizontal and strike towards all points of the compass, changing their direction again and again. They often follow sinuous courses, but sometimes run more straight and keep their direction for considerable distances. They thicken and thin repeatedly and rapidly, while giving off branches (fig. 14) at high and low angles, or often anastomose in complex manner so as to form networks of veins. Often the veins appear to end abruptly. Not seldom they run out into thin lines or streaks which may become imperceptible to the naked eye.

1) S. J. Shand, **85**.

The contact with the surrounding rocks as seen with the naked eye generally appears to be abrupt, but on microscopical investigation often proves to be otherwise.

The veins vary in width from 1 mm. or even less up to 20 m. A dyke of this width has been observed by Messrs. HALL and NEL on Witkop, which so far is the strongest found in the district. The veins always contain many inclusions. These in places become so numerous that they make up 80 % or even more of the total bulk of the veins, the vein-rock then being a breccia, the cement of which is made of pseudo-tachylyte. In the thicker veins the large inclusions are often perfectly rounded and then resemble boulders. The majority of these larger inclusions at each locality consists of the rock which the vein there traverses, but a smaller or larger percentage of them may consist of rocks which are found at some distance. Thus, e.g. on Vleispruit, veins of pseudo-tachylyte cutting across granite contain a fair amount of large inclusions of epidioritized gabbro, which rock at a distance of 50 m. forms a strong dyke across the granite and is likewise traversed by pseudo-tachylyte. Again at Broodkop a network of veins of pseudo-tachylyte is found in gneiss and contains a good number of inclusions of a gabbro which at a distance of about 30 m. is seen as a dyke cutting across the gneiss. This dyke is also cut by pseudo-tachylyte. In fact in any of the somewhat thicker veins inclusions were observed, derived not only from the country-rock at that spot, but also from rocks, which were found to occur at distances up to 100 m. or more. The inclusions of the country-rock in the veins, where derived from rock occurring at the spot are generally turned and shifted in their position. This can be seen very well at Broodkop. The network of veins of pseudo-tachylyte in the gneiss is so close there, that the entire rock resembles a conglomerate made of boulders of gneiss cemented together by a matrix of pseudo-tachylyte. Outside the veins the schistosity in the gneiss has a definite strike about E.-W., but in the enclosed boulders the schistosity runs in most varying directions.

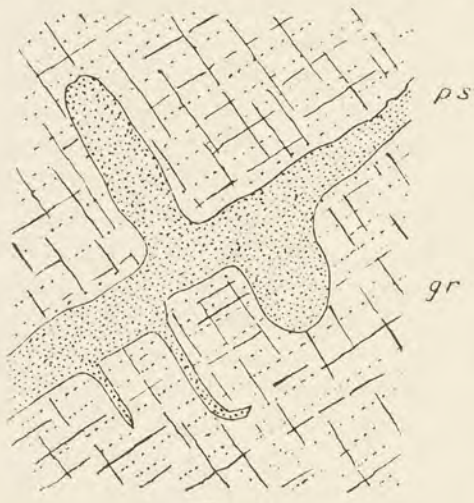

Fig. 14.

Vein of pseudo-tachylyte with apophyses in somewhat gneissic granite at the boundary between Klipfontein and Zijferfontein. *gr.* granite, *pst.* pseudo-tachylyte. — Approx. scale 1 : 20.

This proves that the mobility of the pseudo-tachylyte was high enough to allow the boulders or fragments of country-rock taken up from the walls of the veins and incorporated in the pseudo-tachylyte, to be turned round freely in all directions. The authors believe that by the joint action of rapid movements or flow in the pseudo-tachylyte, when still fluid, and by the corroding influence of this melt on the material of the inclusions, the round shape of many of them can be explained. The smaller inclusions in the pseudo-tachylyte may consist of fragments of rocks, or also of single salic minerals such as quartz, felspar or nepheline taken up from the surrounding country rock. Femic minerals are rarely found amongst them.

The prevailing colour is black on fresh fractures, as e.g. near Parijs, and at the majority of the other localities, especially at those in the granite-area. The pseudo-tachylyte has somewhat the external appearance of a dense, more or less vitreous opaque basaltic rock ; other colours than black, although not wanting, are rarer. A grey colour was observed in several of the veins cutting quartzite, alkali-granite and nepheline-syenite in the Witbank area ; a light grey colour is found in the veins in the gneiss at Broodkop. In the latter case the pseudo-tachylyte is semi-transparent. The weathered surface of the pseudo-tachylyte has almost without exception a peculiar whitish or grey coating, which is not quite smooth, and often shows the smaller inclusions protruding.

Occurrences.

Occurrences of pseudo-tachylyte have been examined and specimens collected at the localities enumerated in the following table (see next page). This gives an illustration of the many varieties of rocks in which veins of pseudo-tachylyte occur, and, if used with the map [1]), helps to form an idea of the great extent of the tract of country more or less riddled with these veins. It appears that the occurrences of pseudo-tachylyte are most crowded in the marginal portions of the Vredefort granite-area and in the encircling girdle of sediments near the contact with the granite ; this is, however, not proved with certainty.

Nature and Origin of the Pseudo-tachylyte.

Most of the occurrences could, in the field, very well be taken for true injections of a basic, say a tachylytic, rock. Certainly the curious way in which the veins vary in thickness in a thoroughly irregular manner, dwindle down to microscopic dimensions and then increase in size again, attaining thicknesses of 10 cm. or more, and anastomose in highly irregular fashion is striking, but examples of igneous veins which behave in a similar way are not wanting. Equally, the manner in which these veins are always crowded with fragments of the invaded country-rock, making them look at many

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1) The localities indicated by black dots on the map are those, in which the occurrence of pseudo-tachylyte has been observed by the authors, but they feel sure that the map would show a very dense system of dots over the entire area, so far as it is not covered by younger strata of the Karroo System, as soon as all the spots in which flinty crush-rocks in reality occur had been indicated.

The detailed mapping of Mr. L. T. NEL, M. Sc., of the Geological Survey, has already added over 600 further examples not shown on the authors' map.

Rocks, cut by veins of Pseudo-tachylyte.	Localities	Remarks
Vredefort Granite, gneissic granite and pegmatite.	Vredefort, Parijs, Klipfontein, Zijferfontein, Kopjesfontein, Vleispruit, Witkopjes, Lesuto's Kraal, Rietpoort, Kopjeskraal, etc. etc.	Veins of Pseudo-tachylyte are found practically everywhere in the area occupied by the Vredefort mass.
Biotite-gneiss.	Broodkop.	
Amphibolite and other schists of the Swaziland System.	Blaauwboschpoort.	A fine specimen was collected in one of the prospecting shafts, showing amphibolite injected by veins of aplite and pegmatite, both rocks being cut again by veins of pseudo-tachylyte.
Large Xenolith of Granite.	Tweefontein.	This xenolith forms a large mass floating in hybridised gabbro.
Gabbro and Gabbro-diabase.	Vleispruit, Broodkop and Kafferkop.	
Hybridised Gabbro.	Tweefontein.	
Epidioritised gabbro, marginal intrusion in granite.	Witbank, Twinkopjes on Rietpoort-East.	
Epidiorite, sill in Lower Witwatersrand Beds.	Witbank, Kopjeskraal and Rietpoort.	
Diabase, sill in lower portion of Upper Witwatersrand Beds.	Reebokkop, part of Aasvogelrand.	
Arfvedsonite-soda-granite.	Witbank, Koedoeslaagte.	
Canadite	Witbank, Koedoeslaagte.	
Basal Amygdaloid.	Witbank, Kopjeskraal, Rietpoort.	
Orange Grove Quartzites.	Witbank.	
Hornfels of group of Water Tower Slates, Lower Witwatersrand.	Witbank, Kopjeskraal, Rietkuil.	
Hornfels of Hospital Hill group, Lower Witwatersrand.	In the Baviaansrand on Witbank and its north-eastern extension on Kopjeskraal.	
Hornfels of upper portion of Lower Witwatersrand.	Koedoeslaagte.	
Quartzite and indurated shale of Main Bird Reef Series, Upper Witwatersrand.	Reebokkop, portion of Aasvogelrand, Goede Hoop, Brakfontein.	
Quartzite and indurated shale of Upper Witwatersrand.	Witkop.	
Kliprivier Diabase, Ventersdorp System.	Smal in de Weg.	

places more like a breccia than anything else, is not usual, but true igneous rocks may afford the same peculiarities [1]). On this account there was no reason to doubt their igneous character. More doubt was aroused by the fact that in some places the veins of pseudo-tachylyte apparently run out into streaks, along which the rocks have been more or less crushed. Such occurrences, where in the field a certain connection could be observed between stress-zones and veins of pseudo-tachylyte, are not numerous ; as examples may be cited the veins on Zijferfontein in the granite, at Kafferkop on Groot Eiland near Parijs in a dyke of gabbro-diabase; on Rietpoort and on Brakfontein in a sill of epidiorite. Examples, where the veins of pseudo-tachylyte apparently cut clean across the invaded rocks and behave exactly like true igneous veins, are so much more numerous, that from observations in the field alone little doubt remained as to the true igneous nature of these veins. Yet the striking phenomena of crush and shattering of the country-rocks, with which the veins of pseudo-tachylyte on Brakfontein are evidently connected, first induced one of the authors to surmise that next to true igneous veins of pseudo-tachylyte flinty crush-rocks play a role in the Vredefort Mountain Land. It was through microscopic examination, however, that the authors recognised the true nature of the veins of pseudo-tachylyte as flinty crush-rocks.

The authors now hold that the pseudo-tachylytes throughout the Vredefort area are not true igneous rocks, and the veins in which these rocks are found not true igneous veins. The tremendous forces wich have led to the updoming of the Vredefort granite-mass, at that time buried under a weight of sediments about 13000 m. thick, met with an equally great resistance when accomplishing their work. This powerful action and reaction must have generated in the affected rock-bodies, the Vredefort Granite and its cover of sediments, very great pressure. The latter which appears to have been not oriented, but acting in all directions (omnilateral or hydrostatic), caused the rocks to be crushed without much shearing ; along planes of somewhat minor resistance the rocks were crushed, triturated and pulverised. The heating effect of this extraordinary mechanical work has been very great and in places it was great enough to raise the temperature of the triturated rocks above their fusing point. The fused rocks solidified again as pseudo-tachylyte, which thus becomes a true flinty crush-rock. The fusion was rarely quite complete and the numerous inclusions are doubtless fragments of the triturated, shattered and crushed rocks, which escaped complete destruction and fusion. The molten matrix or magma, once generated, could move and behave as a true igneous rock. It could be injected in cracks along which no trituration or mylonisation had taken

1) F. E. WRIGHT, **93**, pp. 277 and 278 describes veinlets of monchiquite-camptonite 0.2—1 mm. thick cutting essexite, which are crowded with fragments of the invaded rock ; judging from the figures 5, 6 and 7 on Plates IV and V in WRIGHT's paper they much resemble equally minute veinlets of pseudo-tachylyte cutting nepheline-syenite, granite or other rocks in the Vredefort area.

place, forming in this way clean veins with sharp contact borders ; it could also penetrate into the cracks of the triturated and shattered portions of the rock and there loosen and incorporate as boulders, portions which had already been semi-detached. Everywhere following the lines of minor resistance the molten mass could ramify and form intricate networks ; it would have a corroding influence — surely a selective one — upon the walls of the veins and on the inclusions. Finally as the temperature slowly fell the magma could crystallise as any other true igneous rock.

In the case of rapid cooling it would solidify as a vitreous or semi-vitreous rock ; cooling somewhat more slowly crystallites or spherulites would develop in the groundmass ; cooling still more slowly larger phenocrysts might crystallise in a denser groundmass, and rocks resembling lavas such as e.g. basalts, might be formed.

Thus for the greater part the flinty crush-rocks must, in the authors' opinion, have been generated at or near the spots where they are found now, and must have been formed at the cost of the very same rocks whose place they have taken, and in which they are now seen as veins.

However, by its probable great mobility, if once generated and well fluid, the magma of the flinty crush-rocks may have travelled a good distance away from the rocks, from whose pulverised portions it was actually made. During this movement the molten magma may have incorporated and also transported fragments of all the different rocks, which it happened to meet and to cross. Consequently the chemical composition of the flinty crush-rock need not of necessity show a great analogy to that of the rocks in which it is found as veins ; but where the veins occur in a big uniform body of a certain rock, as e.g. in the Vredefort Granite, such an analogy certainly may be expected to exist.

The authors now discuss how far their opinion about the nature and the origin of the pseudo-tachylyte is supported by the observed facts.

a. Widespread effects of pressure in the rocks throughout the Vredefort area. Crush-zones and mylonised zones Effects of strong pressure are unmistakably present in all the rocks of pre-Karroo age which take part in the building up of the Vredefort Mountain Land. One of the authors has examined slides of granite from nineteen widely spread localities in the Vredefort granite-area. In only four of these were the effects of crush indifferently developed; in the fifteen remaining such phenomena were strongly marked. The crystals of quartz are often cracked and converted into a mosaic of small grains, the twin-lamellae of the plagioclases are frequently bent and broken, while undulatory extinction is prevalent both in the crystals of felspar and in those of quartz. The flakes of biotite are not rarely bent and distorted. Zones, i.e. undulating planes, along which the granite is particularly strongly crushed, intersect the rock apparently in all directions. The quartz in the granite is always more cracked than felspar. When the rock in these crush-zones is ground very fine, it is converted into a powdery aggregate or rock-dust, in which the constituent minerals are no more clearly recognisable ; the crushed rock then passes into a mylonite. Such narrow crush-zones and mylonised zones not seldom run more or less parallel one to the other and together form broader zones in which the disintegration and grinding of the rocks is very conspicuous. Where veins of pseudo-tachylyte occur in such portions of the rock, they run parallel to, and are intimately connected with, the crush-zones. It is a remarkable fact that in the mylonised zones of the rock black specks, probably of magnetite, are abundant much more than in the non-crushed rock, whereas other femic minerals appear to have been more completely destroyed than salic ones [1]). One has the impression as if the magnetite had been newly formed out of material derived from the destroyed femic minerals. Sometimes the mylonised zones, where they get very thin, run into cracks, in which very little crushed material is found, but which in thin sections are conspicuous by rows of black specks.

Microscopical examination of rocks other than granite has led to corresponding results and has convinced the authors of the fact, that the effects of crush are found throughout the entire Vredefort area, i.e. in the Vredefort Granite as well as in the girdle of tilted sediments encircling it. Fig. 1 on Pl. XVII gives a good illustration of crush in a canadite of Koedoeslaagte.

b. The Crush is not accompanied by much shearing. The crushing, however powerful it may have been, is not accompanied by much displacement or shearing, and the crushed zones often intersect the rock in many directions, one direction not being prevalent over others for great distances. In some cases as e.g. in some gabbros and epidiorites, a certain indication of schistosity is present in the vicinity of the crush-zones and the veins of pseudo-tachylyte, but the rocks rarely show schistose structures in a marked degree and over appreciable distances. Small displacements or micro-faults, however, occur fairly regularly and are best seen in slides ; they may exist even where the crush-zones have thinned out and are prolonged as cracks in which only little or no triturated rock-material is enclosed. Plate XI, fig. 2 shows a micro-fault in nepheline-syenite (canadite) along which some shifting has taken place. This little fault here represents the thinned-out portion or continuation of a broader crush-zone. One gets the impression that the shattering, pulverisation and mylonisation of the rock in the Vredefort area has been caused by some sort of omnilateral or static pressure, comparable in its effects to those of pressure in plastic bodies.

1) QUENSEL, 68 p. 97, found in mylonites of the Kebnekaise area quartz and femic minerals destroyed and recrystallised, while the felspars were mechanically affected and cataclastic, but not recrystallised.

An exceptional case is illustrated in Pl. XIX, fig. 2 of a schistose gabbroid rock of the Twinkopjes on Rietpoort north of Parijs. The gabbro is epidioritised, perfectly sheared and mylonised and largely, according to our opinion by fusion, converted into a flinty crush-rock or pseudo-tachylyte (black).

c. The effects of crush increase in intensity in the vicinity of the veins of pseudo-tachylyte and the crush-zones. In the portions of the country-rock which adjoin the crush-zones or the veins of pseudo-tachylyte the effects of crush are as a rule more strongly marked than at a distance from those zones. Not rarely under such conditions the rocks are quite cataclastic and riddled by systems of micro-faults, and although the proper crush-zones possess fairly sharp outlines, there is under the microscope generally a more or less gradual passage discernable between comparatively little crushed rock and the entirely crushed or triturated zones.

Beautiful examples are afforded by the canadites on Witbank and Koedoeslaagte. In highly cataclastic portions of those rocks adjoining crush-zones and veins of pseudo-tachylyte the effects of pressure under the microscope are strikingly illustrated (Pl. XVII, fig. 2) by the development of systems of micro-faults of delicate beauty crossing crystals of albite. Quartzites of the Main-Bird Reef Series on Goede Hoop are close to veins of pseudo-tachylyte intensily crushed. The quartz-grains are cracked and where they touch one another triturated and converted into rims of a fine mosaic passing into rock-dust (Pl. XXII, fig. 2 and 3).

d. The inclusions in the pseudo-tachylyte all show the effects of powerful crush, and also of corrosion by incipient melting. According to the authors the inclusions in the pseudo-tachylyte are fragments of rock or minerals from rock-material in the crush-zones which have escaped total destruction, both during the process of trituration and during the subsequent fusion of the bulk of the triturated mass. If this is really so, then the fragments must show both the effects of powerful pressure and of corrosion by melting. This is exactly what the inclusions show without exception. Among slides of pseudo-tachylyte of the Vredefort area from widespread localities the authors failed to find any instance where the majority of the inclusions in pseudo-tachylyte did not show results either of crush or of incipient melting or both. Such phenomena have already been described and well illustrated elsewhere, e.g. in the memoirs of JEHU and CRAIG [1]) on the flinty crush-rocks of the Outer Hebrides.

1) Messrs. JEHU and CRAIG, in their second memoir on the geology of the Outer Hebrides, dealing with South Uist and Eriskay (42) give valuable additions to our knowledge on flinty crush-rocks and their origin, which had already been greatly extended by

Yet the authors consider it worth while to give a few additional striking instances.

The figures in Pl. XX respresent inclusions of felspar and quartz in a vein of pseudo-tachylyte occurring in Vredefort Granite near Parijs which show the effects of crush very well and are rounded, corroded and partly disaggregated by incipient melting.

Figure 3 in Pl. XXI shows a cracked grain of quartz, occurring as an inclusion in a vein of pseudo-tachylyte which cuts gritty Government Reef quartzite on Witbank. Besides being cracked the grain is triturated in places and has lost its sharp outlines by corrosion and melting.

Not rarely the inclusions are elongated and torn out in one direction, as if they had been viscous and then the pseudo-tachylyte shows flow-structure in the same direction (Pl. XXI, fig. 2).

e. Triturated or mylonised zones pass into veins of pseudo-tachylyte. Sometimes the fine-grained portions of triturated rock-material pass abruptly into pseudo-tachylyte. Larger fragments between the fine-grained material then appear in the pseudo-tachylyte as inclusions. The line of demarcation between the triturated rock-dust and the pseudo-tachylyte is generally well visible and indicated by the presence in the latter of rather thickly crowded black specks, probably of magnetite.

Figure 1 in Pl. XIX shows a thoroughly cracked and crushed canadite found on Koedoeslaagte. The darker streaks are crush-zones made of triturated rock or rock-dust. These streaks unite into a large opaque mass, which consists of pseudo-tachylyte. The passage between the rock-dust and the pseudo-tachylyte is imperceptible in this case.

In a slide of a gabbro of Kafferkop about 5 km. south-south-west of Parys the rock proved to be dissected by numerous cracks along which the rock is triturated. Figure 1 in Pl. XXI shows a large patch of pseudo-tachylyte (black) in this rock and a system of crushed streaks which unite into a larger zone of triturated rock which appears to a great extent to be converted into pseudo-tachylyte (black). Also outside the triturated zones this gabbro throughout shows the signs of having been exposed to strong pressure.

Very similar relations were observed in Basal Amygdaloid on Kopjeskraal, where at many places rock-dust in crush-zones proved to be converted into apparently isolated patches of pseudo-tachylyte and where several narrow crush-zones united into one broader zone which then passed into a vein of pseudo-tachylyte. In the case of a vein of pseudo-tachylyte cutting an epidioritised diabase on Brakfontein the country-rock is triturated

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the facts exposed in their first memoir on the Barra Isles (**41**). The flinty crush-rocks on Eriskay are confined to the base of a great belt of crushed and sheared gneisses and lie immediately upon an important thrust-plane. The country-rock both below and above the thrust-plane is gneiss.

and mylonised and full of cracks and minor crush-zones, in which the rock-material is converted into rock-dust. Between the crushed country-rock and the pseudo-tachylyte in many places an ultra-triturated portion is intercalated in which the rock is ground and also sheared beyond recognition (Pl. XXII, fig. 1). The pseudo-tachylyte (black) sends offshoots into the crushed country-rock and in those it gradually passes into a rock, which is not distinguishable from the ultra-triturated rock mentioned above. The main vein of pseudo-tachylyte has here a kind of selvage which is opaque and almost entirely devoid of inclusions.

f. Contact between Pseudo-tachylyte and Country-rock. In many places the contact between the pseudo-tachylyte and the adjoining country-rock is very sharp, a fact emphasized by SHAND (85 p. 207). Not rarely indeed crystals of felspar or other minerals at such contacts are cut sharply across as if by a knife. From these facts SHAND concludes an absence of shearing; the authors are of the same opinion, but admit powerful crushing without appreciable shearing. Wherever the contact is sharp (Pl. XVI, fig. 2; Pl. XXIV, fig. 3) it is believed that the pseudo-tachylyte was generated by fusion of triturated rock-material at some distance, which has moved freely along fissures in the rock, and then been injected into such portions which by pressure had been coarsely crushed without shearing and without becoming finally triturated. In such cases then the molten crush-rock moved some distance away from the spot where it had generated in crushed zones, and then solidified probably relatively rapidly, causing the corroding effects of the molten mass on the walls of the country-rock to be very small or wanting.

In the majority of cases observed by the authors, however, the contact was not found to be sharp.

First of all the veins of pseudo-tachylyte often send out curved embayments (Pl. XXIII, fig. 2) and offshoots or apophyses into the country-rock. The latter may end blind in small cracks or run out into narrow crush-zones which then form the continuation of such offshoots. In one case where a vein of pseudo-tachylyte cuts across cordierite-biotite-hornfels of the Hospital Hill Series on Kopjeskraal several such offshoots were observed under the microscope, although in the field the impression was that the hornfels had not been crushed at all and had been cut clean by the vein.

Further, in many instances along the wall of the vein a gradual passage exists between the pseudo-tachylyte and the country-rock, such that anastomosing offshoots cut from the former into the latter so as to form a kind of network which gradually gets wider and finally comes to an end. Near the junction the country-rock shows all stages of disaggregation, corrosion, solution and fusion. Figure 1 in Pl. XXV illustrates a good instance in a vein cutting Government Reef Quartzite on Witbank. The junction is not well-defined, the quartzite being entirely crushed, while the larger and smaller grains now form a complicated mosaic of triturated quartz-fragments. It is riddled with crush-zones in which it is finely ground and triturated. Offshoots penetrate from the pseudo-tachylyte into the quartzite along sinuous courses ; they are intimately connected with the ultra-triturated portions of the crush-zone, the latter apparently passing without marked boundaries into the former. However, under the microscope the pseudo-tachylyte is always richer in specks of magnetite than the crushed quartzite; minute needles probably of an amphibole are often present in the pseudo-tachylyte, but wanting in the rock-dust.

The somewhat gneissic granite on Koppiesfontein is riddled by a complicated system of narrow and wider veins of pseudo-tachylyte. Under the microscope this granite proves to be entirely crushed (Pl. XXIII, fig. 1). Lenticular and oval portions of little altered granite are surrounded by totally crushed and triturated granite-material. Pseudo-tachylyte appears to be intermingled with this rock-dust in a most capricious way. The former is not easily distinguishable from the latter and only by using a very small diaphragm numerous fine needles with a high index of refraction became visible in the pseudo-tachylyte, which probably consist of amphibole. These are wanting in the granite-dust. Near the contact with thicker veins of pseudo-tachylyte the crushed granite is half fused and quite disintegrated. Offshoots of the former penetrate far into the rock and neither in those nor in the isolated patches of pseudo-tachylyte farther from the contact do clear lines of demarcation exist between the pseudo-tachylyte and the crushed granite.

In this rock both crush-zones and veinlets of pseudo-tachylyte in places run out into and join much thicker veins of pseudo-tachylyte.

The authors are of opinion that this peculiar type of contact which is of frequent occurrence in the Vredefort area, can be well explained only in case one admits that by powerful pressure the rock was crushed, partly triturated and converted into an ultra-mylonite or rock-dust, and in places fused. Fusion occurred wherever by this powerful mechanical action the temperature was sufficiently raised. The molten portions may remain isolated within the crushed but not molten rock, and may solidify there as patches of pseudo-tachylyte of various shapes and dimensions ; the patches of molten rock may also unite together, form larger veins in which the molten rock may flow, and behave as a true injected igneous rock, and finally solidify perhaps at a considerable distance from its points of origin.

g. S e l v a g e s. An argument in favour of the explanation given by the authors for the origin of the veins of pseudo-tachylyte can be derived from the erratic occurrence of selvages bordering those veins.

In those instances where the completely crushed and triturated country-rock passes almost imperceptibly into a flinty crush-rock rich in corroded fragments of the country-rock itself no trace of selvages are found at the margins of the veins (Pl. XXIII, fig. 1 and 2). This proves that, just as could be expected on the author's surmise, no difference in temperature of importance existed between the triturated and heated country-rock and its fused portion i.e. the molten pseudo-tachylyte or pseudo-tachylyte magma ; the pseudo-tachylyte magma solidified at the same spots, or nearly so, where it had originated as an ultimate product of trituration and consequent heating and partly fusing of rock-material.

In those instances, however, where the veins of pseudo-tachylyte cut clean through the rocks, selvages are as a rule well developed indicating that the country-rock was considerably cooler than the injected pseudo-tachylyte magma. Here the pseudo-tachylyte magma which had originated, some distance away, from the complete trituration and fusing of rock-material travelled thither and got injected in the cooler non-triturated rock in which it is now found solidified. Veins of pseudo-tachylyte with well developed selvages almost invariably carry inclusions of rocks foreign to their encasing country-rock.

h. Microscopic Structure of the Pseudo-tachylyte. Under the microscope the pseudo-tachylyte always consists of a fairly uniform groundmass or matrix in which are embedded inclusions of different rocks and minerals, often in considerable quantity. As stated above these inclusions may be derived from the country-rock in the immediate vicinity, i.e. from the walls of the veins, or they may have been transported over smaller or larger distances by the fused matrix of the pseudo-tachylyte. The inclusions show the effects of pressure ; they are more or less crushed and undulatory extinction prevails. The authors believe that the straining, cracking, and crushing occurred before fusion set in.

The inclusions, moreover, are more or less corroded and often elongated and torn out in one direction, which then coincides with the direction of flow visible in the matrix. They are evidently in many cases fixed in the very act of being incorporated by solution and fusion in the molten matrix of the pseudo-tachylyte (Pl. XXIII, fig. 1 and 2). Femic minerals are very rare among the inclusions ; it appears that they were attacked and taken up by the molten pseudo-tachylyte before the more salic minerals ; probably their iron-content served as a source from which the numerous specks of iron-ore in the pseudo-tachylyte were formed. In some instances, where microscopic veinlets of pseudo-tachylyte cut across rock containing femic minerals, the matrix is more heavily charged with magnetite at those spots where femic minerals were cut across than elsewhere (fig. 15). It appears that this process of destruction of femic minerals such as amphibole, aegirine, biotite is already active in the mylonised or triturated rock in the crush-zones before fusion sets in, because in these triturated rocks fragments of those minerals appear to be very scarce, whereas the triturated material is not seldom rich in specks of magnetite, much more so than the non-crushed rock (compare p. 99).

The groundmass or matrix of the pseudo-tachylyte is generally crowded with small black specks, taken to be magnetite, which may be so abundant that the rock becomes only very little transparent and not resolvable under

Fig. 15*a* and Fig. 15*b*.

Veinlet of pseudo-tachylyte cutting crystals of aegirine in a nepheline-syenite. *a*. aegirine, *b*. pseudo-tachylyte.

Fig. 15*b* shows that the crystal of aegirine being cut by the pseudo-tachylyte was not split and thrust aside, but was partly taken up and replaced by the pseudo-tachylyte which became charged with specks of iron-ore.

the microscope even with high powers. Such an almost entirely opaque variety was observed e.g. at Vleispruit, where it cuts granite and gabbro, in some of the veins in nepheline-syenite on Koedoeslaagte, in a vein cutting hornfels at Hattings Shaft on Witbank, in some of the veins in gabbro at Kafferkop near Parijs, in others cutting Basal Amygdaloid on Rietpoort, and in still others cutting quartzite belonging to the Upper Witwatersrand Series on Goede Hoop. SHAND states, with reference to the pseudo-tachylyte cutting granite at Parijs, that this rock in the smaller veins is more opaque than in the wider ones, and the authors find that this also holds good elsewhere.

The great majority of the pseudo-tachylyte is less opaque and can be resolved under the microscope, but in their examination a difficulty arises from the minuteness of the crystals which separated from the matrix. The following description of the microscopic characters of a vein cutting granite near Parijs may serve as a typical example ;

The rock consists of a groundmass or matrix in which are embedded numerous inclusions of oligoclase, orthoclase and quartz ; they are rounded and their margin is often embayed.

The xenoliths of quartz are, without exception, much crushed and show mosaic-structure under crossed nicols.

The twin-lamellae of the felspar are often bent and the crystals cracked. The number of cracks is less than in the quartz-crystals ; and instead of a mosaic, a breaking up into large fragments occurred ; these are connected by narrow zones filled with crushed felspar-pieces or felspar-powder.

The character of the inclusions and especially the frequent occurrence among them of grains, partly consisting of quartz, partly of felspar, indicate that the inclusions are derived from granite. Then the question arises whether amongst them also fragments of other granitic constituents occur. This question has to be answered negatively. It is significant that apart from a few small crystals of zircon, no minerals other than quartz and felspar are found among the inclusions. Femic minerals such as biotite and amphibole are entirely absent. Not rarely, however, the matrix shows aggregates of densely crowded minute crystals of amphibole with much magnetite, which probably were formed at the expense of dissolved inclusions of femic minerals.

The matrix in so far as it has crystallised consists of felspar, amphibole and magnetite The crystals of felspar rarely show sharp outlines, but are recognisable by their low interference-colours; several are elongated and lath-shaped and then show a faint indication of twin-lamellae, others are more square-shaped and then devoid of twin-lamellae. The index of refraction of the latter is lower than that of the Canada balsam. Presumably the felspars are made up of an acid plaglioclase and orthoclase.

Amphibole is present in slender prisms, often somewhat rounded and without good crystal outlines. The pleochroism shows colours from yellowish-green to bright sap-green; the angle of maximum extinction is 20°. Cross-sections showing the characteristic cleavage of amphibole could not be observed. The crystals are slightly concentrated around the inclusions and not rarely penetrate them.

Magnetite is present as dust, but also as triangular and quadratic crystals with perfectly sharp outlines, indicating well-defined although almost submicroscopic octahedra.

At other localities, where rocks other than granite may have been intersected, the general microscopic habit remains much the same. Magnetite-dust and minute prisms of a greenish mineral, probably amphibole, are the most characteristic components of the groundmass, besides tiny laths of plagioclase, and rarely also small flakes of biotite may be present.

Among the inclusions quartz is as a rule prevalent and the minerals found as inclusions are by no means wholly representative of the main constituents of the invaded rock. The following instances may be quoted.

1. In vertical strata of cordierite-biotite-garnet hornfels of the Hospital Hill Series on Kopjeskraal occurs a vein of pseudo-tachylyte (Pl. XXIV, fig. 3), rich in inclusions of crushed quartz, which, by their size, prove that they cannot have been derived from the hornfels, but must have been transported, probably from the bars of quartzite of the Hospital Hill Series which crop out at a distance of at least 100 m. On the other hand minerals such as cordierite, biotite and garnet, which are the main constituents of the hornfels, are absent among the inclusions of this pseudo-tachylyte.

2. Another vein, cutting a large xenolith of granite, in hybridised gabbro on Tweefontein, carries inclusions of quartz, orthoclase, microperthite, oligoclase and magnetite all derived from the granite.

3. Veins of pseudo-tachylyte cutting canadite on Koedoeslaagte in places only contain crystals of albite in a condition of solution, in other places also acid plagioclase, orthoclase, quartz and basic plagioclase, of which the two last mentioned minerals do not occur at all in the canadite, and must have been transported from a good distance.

4. The pseudo-tachylyte in a vein cutting granite on Vleispruit contains inclusions of orthoclase and oligoclase, and also fragments of a basic plagioclase evidently derived from a dyke of gabbro which is cut by the same vein at a distance of about 50 m.

5. A vein crossing gabbro at Kafferkop on Groot Eiland, which occurs as a powerful intrusion in granite, contains inclusions of basic plagioclase derived from the gabbro, but also of quartz and micropegmatite, both derived from the granite.

In the great majority of occurrences in the Vredefort area examined by the authors, the matrix of the pseudo-tachylyte shows an incipient crystallisation very similar to the one described above from Parijs, but in rare instances the crystallisation is more perfect. Thus among the numerous veins cutting canadite on Koedoeslaagte, one was found in which the matrix was holocrystalline and consisted of sheaves of acicular prisms and needles of amphibole embedded in a mat of minute laths of plagioclase and magnetite-dust.

Again in the south-western portion of Zijferfontein a vein of pseudo-tachylyte cuts granite; here the matrix is well crystallised (Pl. XXIV, fig. 1) and forms large spherulites of felspar (possibly also quartz). Its colour is grey and dusted over with small specks of magnetite. The inclusions consist chiefly of crushed grains of quartz.

Finally on Tweefontein at the boundary with Smalfontein pseudo-tachylyte cuts an amphibolitised gabbro. In the former, besides numerous inclusions, phenocrysts of labradorite and pyroxene occur in a matrix consisting of small grains probably of a greenish amphibole and laths of plagioclase, and showing intersertal structure; thus the pseudo-tachylyte is here entirely crystallised and resembles a basaltic rock.

In all cases, where the groundmass is more or less crystallised, these crystals do not show any signs of crush; neither the sheaves of amphibole nor the spherulites of felspar nor any other crystals formed by crystallisation of the matrix of the pseudo-tachylyte are bent, broken, dislocated or in any way deformed by pressure.

Chemical Composition.

The chemical composition of the pseudo-tachylyte from five different localities in the Vredefort area is given in the following table, the columns I—VI of which represent resp.:

I. Pseudo-tachylyte cutting Hornfels, Koedoeslaagte.
II. „ „ cutting Nepheline Syenite, Koedoeslaagte.
III. „ „ cutting Gabbro, Anna's Rust.
IV. „ „ cutting Quartzite, Goede Hoop.
V. „ „ cutting Granite, Parijs.
VI. Granite, Parijs, cut by Pseudo-tachylyte of V.

Analyses I to IV — by H. G. Weall, Government Laboratories, Johannesburg. Analyses V. and VI. — by H. F. Harwood (see Shand's paper).

Analyses of Pseudo-Tachylyte.

	I	II	III	IV	V	VI
SiO_2	62.00	55.90	52.70	44.90	66.95	67.72
TiO_2	.60	.30	.45	.55	1.75	1.36
Al_2O_3	11.85	14.60	7.60	14.55	15.06	15.74
Fe_2O_3	2.50	9.90	0.50	2.90	1.58	1.04
FeO	11.30	5.45	8.35	24.50	2.18	2.33
MnO	—	.10	.15	.05	0.03	0.02
CaO	1.70	1.60	13.95	.35	3.25	2.93
MgO	3.30	1.50	13.40	4.00	1.38	0.99
Na_2O	1.40	7.45	1.15	.25	4.32	4.49
K_2O	1.45	2.60	.35	1.20	2.85	2.21
P_2O_5	—	.20	.15	.10	0.07	0.11
H_2O(110°)	1.20	.20	.25	1.3	0.12	0.11
Loss on ignition	2.90	.30	1.10	5.2	0.51	0.68
Total	100.20	100.10	100.10	99.85	100.05 [1]	99.78 [2]
Sp. Gr.	2.875	2.86	3.02	2.96		

First of all the wide divergence in chemical composition is conspicuous; this, however, is easily explained, as soon as one admits that the pseudo-tachylyte is the product of ultra-trituration of different rocks and thus is bound to have a chemical composition reflecting the large variety of material from which it originated.

In the case of the pseudo-tachylyte cutting Vredefort Granite near Parijs, at a considerable distance from its margin, the close chemical analogy between granite and pseudo-tachylyte (analyses V. and VI.) is easy to understand, because the latter in this case certainly originated from the triturated granite or granite-dust itself, without admixture of foreign material. In fact the figures of analyses V and VI are so nearly identical, that the participation of rock-material other than granite in the production of the pseudo-tachylyte can be excluded. SHAND's [3]) conclusion that this pseudo-tachylyte has originated from the granite itself through melting appears unavoidable, but the authors are not prepared to endorse SHAND's next conclusion, that the melting has been caused not by friction and shearing but by shock, or alternatively by gas-fluxing. They are of opinion that the melting was the ultimate result of pressure, causing first cracking and some shearing, then trituration and some mylonisation, and finally ultra-trituration and fusion [4]).

1) and in addition S, 0.12; BaO, 0.05; and Cl, trace.

2) and in addition S, 0.02; SrO, 0.03; BaO, 0.01; Cl, trace.

3) S. J. SHAND, **85** p. 216.

4) Results lately obtained in boreholes in California give an experimental confirmation of the theoretically admitted possibility of the origin of flinty crush-rocks by trituration and partial fusion of pre-existing rocks, under the influence of powerful mechanical stresses. N. L. BOWEN and M. AUROUSSEAU, **6***.

In all other cases (Analyses I to IV) there is no such close analogy between the chemical composition of the pseudo-tachylyte and the rock in which it is found. This is just what could be expected. None of the rocks which are cut by the pseudo-tachylyte veins represented in Columns I to IV are in bulk comparable to the mass of the Vredefort Granite. The pseudo-tachylyte in those veins was certainly formed not only from the triturated material of their immediate country-rocks, but also from other rocks which crop out or occur in the neighbourhood and are also cut by the same veins. Consequently the composition of the pseudo-tachylyte in each case must differ more or less from that of the invaded rocks in which it solidified. Thus the pseudo-tachylyte cutting canadite on Koedoeslaagte (Analysis II) gives a composition different from that of the canadite itself (compare page 82), and the same holds good for the pseudo-tachylyte cutting gabbro on Anna's Rust (Compare Analysis III in the above table with the analysis of gabbro on page 42).

Yet in several cases some of the characteristics of the invaded rock are reflected in the composition of the pseudo-tachylyte :

Thus the pseudo-tachylyte which cuts canadite on Koedoeslaagte is richer in soda than any of the others, a characteristic feature which it has in common with the invaded canadite ; again the high content of MgO and CaO in Analysis III of the pseudo-tachylyte cutting gabbro is a feature of the last named rock also.

The high content of iron shown in Analyses I, II and IV is easily explained by the fact that highly ferruginous sediments are found in every case close to where the analysed samples were collected. These ferruginous sediments are no doubt cut by the same system of veins from which the samples were taken.

Well within the granite-area near Parijs (analysis V) the pseudo-tachylyte is poor in iron, because it occurs in, and is derived from, a large rock mass equally poor in iron. (Analysis VI).

Opinions of other authors on flinty crush-rocks of different localities.

Flinty crush-rocks have been described and recognised as the end-product of crushing and mylonisation mostly accompanied by incipient fusing in rocks subjected to powerful dynamic action, by SIR TH. HOLLAND [1]) from Peninsular India, by C. T. CLOUGH [2]) from the Cheviot Hils, by PEACH and HORNE [3]) from the North West Highlands of Scotland, by H. BACKLUND [4]), from the province of Olavarria in the Argentine Republic, by CLOUGH, MAUFE and BAILEY [5]), from Glen Coe, by T. J. JEHU and

1) TH. HOLLAND, **33**.
2) C. T. CLOUGH, **13**.
3) B. N. PEACH and P. HORNE, **64**.
4) H. BACKLUND, **2**.
5) C. T. CLOUGH, H. B. MAUFE and E. B. BAILEY, **14**.

H. M. CRAIG [1]), from the Outer Hebrides. They are also described as *purée parfaite* being an ultimate product of mylonisation by P. TERMIER et T. BOUSSAC [2]) from Savone and as ultramylonites by QUENSEL [3]) from the Kebnekaise area, without fusion being admitted by these authors as a necessary condition for their origin. Flinty crush-rocks possibly also occur in connection with the overthrusts in the Caledonian mountainchain in Lappland [4]).

SHAND, in the case of the pseudo-tachylyte of Parijs, does not make dynamic action responsible for the origin of that rock [5]). He classifies the known pseudo-tachylytes as follows :

a. Black rocks, composed of crushed material without recrystallisation or any evidence of elevated temperature : Argentine ; Namaqualand ; most Scottish and Indian localities.

b. Black rocks, composed of crushed material, with evidence of high temperature approaching the melting points of some of the constituents, and with beginnings of crystallisation : some Scottish localities, especially Glen Coe, Meall Riabhach, and N. Uist ; some Indian localities(?).

c. Black rocks, which hold inclusions of fragmentary material, but lack proof of origin by crushing ; the temperature exceeded the melting point of felspar, and spherulitic and microlitic crystallisation took place : Parijs.

He further remarks :

"Regarding the evidence from a purely qualitative standpoint, it would seem that we have a complete series of rocks connecting up the pseudo-tachylyte of Parijs with ordinary mylonite, the various links in the series being as follows : Mylonite → fritted mylonite or flinty crush-rock → fused mylonite or pseudo-tachylyte (type b) → recrystallised pseudo-tachylyte (types b and c)."

"Arguing on these lines, it is possible to maintain the view that pseudo-tachylyte is simply an extreme form of flinty crush-rock, the production of which involved a greater generation of heat than usual."

SHAND is of opinion that against this view there are some very weighty arguments. His chief argument is, that at Parijs exclusively the third member of the supposed series occurs, whereas in all other regions mentioned above the first member of the series is abundant, the second much scarcer, and the third limited to a few minute occurrences. A second argument lies in

1) T. J. JEHU and R. M. CRAIG, **41** and **42**.

2) P. TERMIER et J. BOUSSAC, **88**.

3) P. QUENSEL, **68** p. 104.

4) The cataclastic rocks, mylonites and ultra-mylonites in the Torne Träsk area (the *Kakirite* of Svenonius) as well as the perfectly banded *Hartschiefer* of the same area, both described by HOLMQUIST, appear from the photographs to be more or less altered into flinty crush-rocks. (P. J. HOLMQUIST. Die Hochgebirgsbildungen am Torne Träsk in Lappland. Geol. Fören. i Stockholm Förhand. Bd. 32, pp. 913—983, 1911). Compare fig. 10 and 11, Quartz—syenite—mylonite and Cataclastic granite of HOLMQUIST' paper with fig. 1 and 2 on Pl. XIX of this paper.

5) S. J. SHAND, **85** p. 212.

the absence of shearing and cataclastic phenomena in the granite at Parijs.

The authors who did not limit their study of the pseudo-tachylyte to the occurrences at Parijs alone, but examined a very large number of others far spread all over the Vredefort Mountain Land, are not convinced of the weight of these arguments.

They found all the members of the supposed series as defined by SHAND represented in the Vredefort area, and are of opinion that in the case of the third member the rock originated, as in the case of the other members, from the fusion of crushed material, but that in this case the fusion was complete enough to allow the molten rock to flow in cracks and finally to solidify and crystallise at a distance from its place of origin outside the crush-zones, thus forming veins in a country-rock which does not show many signs of crushing, if any. As to the second argument, they find — see pages 98 and 99 — that the great majority of rocks in the Vredefort area, invaded by pseudo-tachylyte, show more or less marked cataclastic structures, and that the cases where the effects of crush are absent near the veins, can be explained by the pseudo-tachylyte having been formed from crushed rocks at some distance, but travelling towards and penetrating fissures and cracks in the non-crushed rocks, in which it is now found solidified.

The flinty crush-rocks described in this chapter from the Vredefort area, however, differ in their mode of occurrence from that of all other known localities in two important respects :

1. They are not derived from one class of rock only, but from a great variety of material, both sedimentary and igneous, of widely different texture and composition.

2. Their total bulk is great, and, as far as can be judged from the descriptions of other localities, appears greatly to surpass the mass of these rocks found anywhere else.

Pseudo-tachylyte and enstatite-granophyre.

Pseudo-tachylyte is found as veins in all rocks of pre-Karroo age with the solitary exception of the enstatite-granophyre.

The authors have not found a single instance of pseudo-tachylyte in the dykes of enstatite-granophyre. Subsequent to the authors' field-work the Geological Survey observed hundreds of veins of pseudo-tachylyte in all formations, the enstatite-granophyre again excepted. Thus the probability is very great that the absence of these crush-rocks in the enstatite-granophyre dykes is not due to accident, but to the fact that pseudo-tachylyte was never formed in them. This means that the dykes are either more recent than or of the same age as the pseudo-tachylyte. Certain petrological similarities between the pseudo-tachylyte and the enstatite-granophyre (see p. 62), specially the apophyses and selvages of the latter, suggest that these rock-groups are more or less closely related in their mode of origin and period of formation.

The enstatite-granophyre described in chapter III, 7, c takes up a peculiar place among the igneous rocks. The combination of small phenocrysts of rhombic and monoclinic pyroxene, plagioclase and biotite with an abundant granophyric groundmass as found in this rock is unusual. The rock is rich in inclusions which show the effects of high pressure in a marked degree, whereas the phenocrysts mentioned above do not show any effects of pressure. The former closely resemble such inclusions as are characteristic of pseudo-tachylyte. In its selvages and apophyses the enstatite-granophyre is more rapidly cooled, and then shows in its petrographic habit a close resemblance to those pseudo-tachylytes in which the matrix has been crystallised chiefly as spherulites.

The authors are in doubt whether the enstatite-granophyre must be regarded as a true igneous rock, formed by the last manifestation of activity of the same deep-seated hidden magma from which the other basic marginal intrusions in the Vredefort area have been originated, or whether it may not be a ,,glorified'' form of pseudo-tachylyte, i.e. a flinty crush-rock on a gigantic scale originating by ultra-trituration and fusion of different rocks [1]) in the zone of intense pressure between the updomed Vredefort Granite and the girdle of uptilted sediments around it. They are inclined to accept the second mode of origin as the more probable one.

An Estimation of the Total Bulk.

It is obviously impossible to give anything like an accurate estimate of the total bulk of the veins of flinty crush-rock in the Vredefort area, owing to their highly irregular shape and distribution ; there are, however, data available sufficiently numerous and reliable to indicate roughly the order of magnitude.

Though occasionally of considerable width, the majority of the flinty crush-veins vary from a few feet in width down to delicate veinlets, so that 25 cm. would be a safe estimate of the average thickness. While locally traceable over great distances, an average length of 30 m. is also conservative. In connection with the vertical persistence, the degree of sculpturing of the Vredefort Mountain Land, the occurrence of these phenomena at almost all altitudes, and the fact that denudation has removed a not inconsiderable thickness of the succession, indicate an original average vertical continuity of 500 m. as not excessive. On this basis a single band of flinty crush-rock represents a bulk of 3.750 cub. m. (in round figures).

The writers endeavoured to note all the occurrences, but in the

1) The chemical analyses of three samples of enstatite-granophyre (page 61) taken from three different localities do not show great differences in chemical composition as could be expected if endorsing this surmise ; this apparent constancy in chemical composition is, however, easily explained, if one takes in account that the localities, from where the samples were taken, are situated in about the same geological horizon viz. at or near the margin between the Vredefort Granite and the Basal Amygdaloid.

circumstances it was not possible to carry out their systematic location ; the number actually observed was two hundred, more or less, which would give a combined bulk of 750.000 cub. m.

This is undoubtedly far too low an estimate, since only the granite and the Witwatersrand System have been taken into account, yet flinty crush-rocks were now and then observed in the Ventersdorp System, while the recent detailed mapping by Mr. L. T. NEL, M.Sc., of the Geological Survey, has added many more occurrences, not included in the above estimate. Mr. NEL has recorded some 650 examples within the girdle of sediments alone, so that the total instances certainly number not less than 800, and most likely very much more. Taking a total of 2000 is a safe estimate, and this would give a bulk of 7.500.000 cub. m.

Assuming that the powerful enstatite-granophyre dyke is a "glorified" or "giant" form of the same crush-phenomenon, its length of 40 km. and average width of 30 to 40 m. would — on the same vertical basis of persistence — add about six hundred to eight hundred million cubic meters to the above figure.

Crush as a Factor in the Genesis of Igneous Rocks.

The conclusion just stated, i.e. that the collective bulk of the flinty crush-rocks is considerable, raises the question, whether dynamic action may not after all be admitted in special cases as a factor in the genesis of igneous rocks.

Flinty crush-rocks and especially those of the Vredefort area at least tend to demonstrate that under particular tectonic conditions rocks can originate from pre-existing eruptives or sediments in circumstances where mechanical action plays an important role.

MALLET [1]) advocated this view as early as 1872, and thus formulated the essence of his theory :

"The heat from which terrestrial volcanic energy is at present derived is produced locally within the solid shell of our globe by transformation of the mechanical work of compression or of crushing of portions of that shell, which compressions and crushings are themselves produced by the more rapid contraction, by cooling, of the hotter material of the nucleus beneath that shell, and the consequent more or less free descent of the shell by gravitation, the vertical work of which is resolved into tangential pressures and motion within the thickness of the shell."

According to MALLET igneous rocks are formed by localised crushing of material of the earth's crust, the heat required for fusion being due to mechanical work performed.

Flinty crush-rocks have not received much attention in the leading text-

1) R. MALLET, **52**.

books of geology, and appear to be regarded as purely local phenomena, of little importance; their detailed study has been conducted in very few areas, mainly in recent years, while their geological importance was certainly not known when MALLET wrote.

The occurrence of flinty crush-rocks in the Vredefort area on a scale which appears unique — to judge from the literature of other examples elsewhere — does show that these rocks can play a significant part. It would seem to be admissible that in regions of exceptionally powerful crustal deformation, say in large mountain-chains, the intrusive rocks which occur in the majority of such chains may be to a smaller or larger extent the result of fusion of pre-existing rocks. The heat necessary for fusion may have been wholly or in part obtained from the mechanical work of crushing of rock-material, due to tangential pressure in the earth's crust in the mountain-chain in *statu nascendi*.

It is true that the majority of the flinty crush-rocks are unlike known types of igneous rocks, but some of them, as for example the type found on Tweefontein, bear a great resemblance to some basalts or andesites. Remembering how little on the whole flinty crush-rocks have been studied, it is quite conceivable that there may be other occurrences of pseudotachylyte that have not been recognized as such, owing to their close resemblance or even identity with types of igneous rocks, though resulting from triturated and ultimately fused older material.

The writers are aware that on grounds that need not be discussed here, MALLET's extreme standpoint has met with little support from the bulk of geological opinion — probably rightly so. Nevertheless, the detailed study of the present area makes it extremely difficult to resist the conclusion that in special cases as the result of very great stress mechanically generated heat can be allowed as an important contributing factor in rock-genesis.

In the writers' opinion the extraordinary and almost unique tectonic history of the Vredefort Mountain Land is such a special case.

CHAPTER IV.

The Metamorphism of the rocks round the Vredefort Granite and its causes.

Since the girdle of Witwatersrand rocks encircling the central granitic area includes both sediments and contemporaneous igneous rocks, it will be convenient to treat the alteration of these different types separately.

It is highly probable that the metamorphic phenomena depend upon complex causes, in which both pressure and heat enter, and that the results are due to a combination of some form of regional metamorphism (independent of intrusive bodies) with thermal (or local) metamorphism (depending upon a large intrusion). This Superposed-[1]) or Poly-metamorphism[2]) indicates that there may be areas which have been exposed to the influence of one or other or even both of these factors; since there are some grounds for believing that this is actually the case, no doubt the most scientific way of dealing with the phenomena would have been to discuss them separately in accordance with their mode of origin. On the other hand, such a presentation involves a good deal of repetition ; also it is by no means easy to differentiate in every case between the several phases of metamorphism and their results.

For these reasons, the following section A is essentially descriptive, and covers all varieties of altered sediments, irrespective of their mode of origin.

The broader aspects of polymetamorphism will be considered in section C of this Chapter.

A. THE METAMORPHISM OF THE SEDIMENTS.

1. *Distribution of the Altered Rocks.*

These extend from the base of the lowest Orange Grove Quartzite upwards and continue — in the area of their maximum development — at least as far as the Bird Reef Amygdaloid, thus comprising not less than the entire thickness of the Lower Witwatersrand System, i.e. more or less 3200 m. (10500 feet). Locally one finds hornfels along a horizon closely corresponding to that of the Main Reef Series, so that probably a small width of the Upper Witwatersrand System also falls within the zone of metamorphism.

Altered rocks are traceable for some 130 km. (81 miles) all round the

1) A term first used in J. J. H. TEALL, **89**, p. 8.

2) This term is due to J. KOENIGSBERGER, **46**, p. 670.

central granite. A belt of intensely altered shales — converted into andalusite- and cordierite-hornfels, or of ferruginous siliceous rocks that have become garnet-amphibole hornfels — runs over a distance of at least 40 km. from the farm Brakfontein — six miles north of Parijs — through Rietpoort, Kopjeskraal, Witbank and further into Leeuwdoorns some 26 km. south-west of Parijs. Very good outcrops lie on the western portion of Rietpoort, and specially on Witbank, where a fine succession of altered quartzite and highly altered slates, i.e. cordierite-hornfels, andalusite-hornfels, garnet-amphibole-hornfels, etc. occupies a width of approximately 6 km.

Altered sediments, notably garnet-amphibole-hornfels, are also found due east of Parijs in the Tweefontein area, on Prospect, 31 km. south-east of Vredefort etc., so that some form of metamorphism can be followed more or less all round the granite, as far as the surrounding sediments have been stripped of overlying Karroo Beds.

The most striking metamorphic effects follow a horizon from the base of the lowest Orange Grove Quartzite to some distance above the main Hospital Hill Quartzite and are most strongly marked within the Hospital Hill Slates. Metamorphic rocks are also found higher up the succession in the Government Reef Series, in the Jeppestown Series and in the Main Bird Quartzite, specially close to the small intrusions of alkali-granite on Witbank, Koedoeslaagte and Schurvedraai, which are described in section *7d* of Chapter III. Occasionally large masses of holocrystalline hornfels and altered quartzite (belonging respectively to the Jeppestown Series and the Main Bird Quartzite) are observed as xenoliths in the alkali-granite of Schurvedraai.

The thickness of the succession which has been metamorphosed varies between wide limits ; in the area of maximum alteration, on Witbank, there is a well exposed series of highly altered rocks measuring approximately 1500 m. (4730 feet) from the base of the Orange Grove Quartzite up to a horizon a few hundred feet above the Main Hospital Hill Quartzite. On Kopjeskraal both the lower and upper quartzites belonging to this horizon form distinct features, separated by a well marked shoulder, consisting of a fairly uniform sequence of andalusite- and cordierite-hornfels between 210 m. (700 feet) and 240 m. (800 feet) thick.

In discussing the physical features of the girdle of sediments (chapter II) attention was called to the high degree of sculpturing determined by the resistant bands of quartzite, but locally (where the metamorphism has been specially strong, as on Witbank) the complexity of the surface-features is accentuated, since the Hospital Hill Slates have passed from soft argillaceous rocks into relatively hard hornfels, so that e.g. the strip of country south-east of the main ridge of Hospital Hill quartzite on Witbank and Kopjeskraal no longer gives rise to a deep valley, but to dissected ground with slopes rising in places almost to the summit of this quartzite (Pl. III, fig. 2).

2. *Mineralogical Composition.*

Taking the altered rocks as a whole, their mineralogical composition — in approximate order of abundance — is as follows :

Quartz, biotite, cordierite, ottrelite, garnet, andalusite, hornblende, magnetite, chlorite, felspar, staurolite, muscovite, tourmaline, zircon, sillimanite and hypersthene.

It would lead too far to discuss the mode of occurrence and microscopic characters of these minerals in detail and the following remarks refer only to some outstanding features of the most important metamorphic minerals :

Biotite. After quartz, this is the most widespread mineral, highly characteristic of all those metamorphosed types, which are represented elsewhere along similar horizons by argillaceous rocks, e.g. the slates of the Hospital Hill and Jeppestown Series ; the mineral is nearly always an intensely pleochroic vivid reddish-brown biotite. Where the original rocks were impure and more siliceous, the biotite is much less plentiful and is frequently associated with garnet instead of cordierite and andalusite, when the colour is no longer vivid red, but has a distinct greenish tone. Where the normal rock carries more quartz and iron ore, its metamorphic phase loses biotite altogether, and develops garnet with or without ferrous silicate hornblende.

Normally the biotite can be recognized during the examination of handspecimens with a pocket-lens, when their highly characteristic glittering appearance is seen to be mainly due to countless minute flakes or laths of this mica. In this respect they strongly recall the intensely altered shales of the Pretoria Series falling within the inner contact belt of the Bushveld Complex (Groothoek type), as well illustrated e.g. by the xenoliths of biotite-hornfels belonging to the Jeppestown Series enclosed in the alkali-granite of Schurvedraai.

In thin sections the biotite is commonly distributed more or less evenly in many roughly rectangular highly pleochroic crystals with irregularly indented outlines and frequently a strongly marked sieve-structure (Pl. XXVI, fig. 1), the latter is due to many inclusions mainly of quartz. In certain coarse types the many small laths of mica are associated with a few large rectangular plates ; these may show a few inclusions of minute grains of zircon associated with strongly marked pleochroic halos (Pl. XXVII, fig. 3 and 4, and Pl. XXVIII, fig. 1 and 2). Such large biotite may be so extensive as to occupy the entire field of view under a magnification of only 15 diameters ; at the same time sieve-structure is so pronounced (Pl. XXIX, fig. 1) that the many inclusions of quartz account for the major portion of the field of view over which a few scattered grains of biotite are optically continuous. The more or less even distribution of the mica is specially noticeable in the true hornfels (mica and quartz) ; where the latter also contains cordierite — specially when this builds large individuals — the biotite flakes often lie round the former, besides forming many small inclusions within it.

Usually the biotite is very fresh and rarely shows alteration-products: in two cases it was observed to pass into delicate whisps of sillimanite (Pl. XXVI, fig. 3), while in a few cases it is altered to pale green chlorite. The former change results in microscopic features closely resembling those described from the biotite-cordierite-sillimanite-gneisses (Malips River Type) of M'Phatlele's Location in the Northern Transvaal, which were derived from shales belonging to the Pretoria Series within the aureole of the Bushveld Complex [1]).

Cordierite. This mineral, very common and wide-spread in beds originating as shales, is very often indicated on weathered surfaces by scattered oval pits or other irregular depressions owing to the ease with which it undergoes alteration. Such pits are often coated with a delicate rusty brown surface lining and may show a linear arrangement; usually the depressions are round a quarter to a third of an inch long, and they produce a highly characteristic pitted appearance in rocks that have been exposed for a long time. Rietpoort, Kopjeskraal, and Witbank, or Leeuwdoorns west of Vredefort, have many outcrops of this kind, specially along horizons between the Lower and Upper Hospital Hill Quartzite.

On fresh fractures the presence of this contact-mineral is often lost, but now and then it is traceable as oval portions faintly marked off from the surrounding area.

Under the microscope cordierite is found in large rounded or oval colourless crystals (Pl. XXIX, fig. 2), separated by a "paste" or groundmass of recrystallised material, composed of intense brown biotite and granular quartz. In other cases the whole section is due to a few large cordierites with no recrystallised matrix. Sometimes a single crystal can occupy the entire field of view under a magnification of only 15 diameters. The mineral has very feeble relief and is riddled with inclusions of biotite, quartz, ottrelite and a few minute tourmaline grains (Pl. XXV, fig. 2, and Pl. XXXI, fig. 3). These inclusions are so numerous that their combined area is distinctly in excess of that due to the cordierite, the isolated portions of which retain optical continuity. Though very liable to be mistaken for quartz the mineral shows a slightly different relief and is also distinguishable from quartz by the biaxial character; pleochroism was not observed. The microscopic characters of cordierite in these rocks are practically indistinguishable from those described in connection with the metamorphic province of the Bushveld Complex.

Ottrelite. This mineral is not seen in handspecimens, but is abundant along certain horizons, e.g. in the Hospital Hill Slates on Witbank. Almost invariably ottrelite forms an inclusion in cordierite.

Under the microscope it occurs as abundant short columnar crystals with high relief and a cloudy appearance. With low power these appear grey, but with a high power show a pale greenish or yellowish green colour,

1) A. L. Hall, **27** and H. Kynaston, **47**.

highly indented outlines, and a few minute inclusions of quartz. Occasional twin-lamellation is observed running with the direction of elongation, while the extinction is straight. Where the individuals are somewhat larger, pleochroism is quite definite.

It may be thought that the ottrelite might belong to a stage anterior to that metamorphism, which resulted in the admitted contact-minerals cordierite, andalusite etc. The extremely intimate association between ottrelite and cordierite makes such a view very doubtful. This is further illustrated by its orderly distribution — by no means exceptional — found in some of the coarse cordierite-hornfelses e.g. on Witbank (Hospital Hill Slate). A matrix composed of more or less evenly scattered biotite and quartz grains is broken up by a large almost circular individual of cordierite (Pl. XXIX, fig. 2). The periphery of the latter is emphasized by a festoon-like border of biotite ; this is succeeded towards the interior by a narrow annular border (concentric) of almost clear cordierite, through which are scattered many minute stumpy needles or columnar crystals of ottrelite, but practically no mica. Then follows the remaining and much greater portion of cordierite which together with the outer annular border, forms one individual. The large interior portion is full of inclusions of much deep-brown biotite, a fair amount of quartz, and a little tourmaline in minute grains, requiring a high power and much patience for their detection. Mostly no ottrelite lies in this centre, or else its proportion is almost negligible. Such phenomena are difficult to reconcile with a conclusion other than of a genetic connection between cordierite and ottrelite.

Garnet. Often this is readily distinguishable in handspecimens, usually with the naked eye even. It is frequently found scattered more or less evenly through the rock in reddish crystals with the familiar rounded outlines. This mode of occurrence is very common in those rocks which originated as siliceous ferruginous bands e.g. certain horizons associated with the Orange Grove Quartzites on Brakfontein near the right bank of the Vaal River, or a certain layer a little above (stratigraphically) the main Hospital Hill Quartzite on Witbank ; the latter garnetiferous rock gives rise to a little waterfall, while passing across the Vaal River. In these instances the garnet is very abundant and may reach dimensions up to a quarter of an inch across. In other cases, notably in some bands belonging to the Water Tower Slates, the garnet is confined to narrow layers, and is found outside these only sparingly in isolated crystals. Instead of carrying garnet in fairly plentiful relatively large crystals, some altered ferruginous rocks contain this mineral in extremely abundant but minute grains (Pl. XXX, fig. 2). The mineral also occurs in the cordierite and andalusite-slates, but is not as a rule abundant in these and rarely visible to the naked eye. It is far more often associated with hornblende (Pl. XXIV, fig. 2, Pl. XXIX, fig. 4) and iron-ore, than with cordierite or andalusite. In a few cases garnet is also met with quite locally in certain layers of quartzite, e.g. within the Main Hospital Hill Quartzite on Witbank, where it forms numerous rounded grains of small size.

The microscopic characters show rounded or nearly hexagonal outlines, frequently minutely indented; a highly developed sieve-structure (Pl. XXIX, fig. 3) is present and due to countless minute inclusions of clear quartz. Often the mineral shows a cloudy interior surrounded by a clear border, very marked for example, in the garnet-hornfels a little above the Hospital Hill Quartzite. In the andalusite-cordierite-hornfels the mineral sometimes has a very regular narrow border (Pl. XXX, fig. 1), which is quite definite when the garnet lies in the groundmass, becomes faint when it lies inside biotite and vanishes when the mineral is enclosed in andalusite. In such cases the outline is crenulated in a manner recalling the appearance of a block of ice in process of melting. Some of the garnet in the altered quartzites is very faintly doubly refractive; this has often been noted when the mineral has a contact-metamorphic as distinct from a magmatic origin. [1])

The great predominance of garnet in such horizons as the Water Tower Slates (Pl. XXX, fig. 2) where it is accompanied by plentiful iron-ore, and in other ferruginous siliceous sediments, suggests that it is a variety rich in iron, a conclusion supported by the fact that it is sometimes highly altered into a network of rusty brown hydrated iron-ore, e.g. in certain horizons of ferruginous layers in the Government Reef Series.

Andalusite. This is the most conspicuous contact-mineral in the field, though more restricted in distribution. Andalusite is most striking in the Hospital Hill Series from the top of the Water Tower Slates to the main Hospital Hill Quartzite, but it is also represented in the coarse intensely altered slates directly above that quartzite, and in the staurolite-hornfels from the Government Reef Series on Koedoeslaagte. Outcrops with large and striking andalusites lie a few yards east of the Potchefstroom main road on Rietpoort a little north of the prominent ridge of Hospital Hill Quartzite, whence similar rocks run westwards across Rietpoort into Kopjeskraal, across the Vaal River into Witbank, and further south-westwards or southwards into Leeuwdoorns.

On weathered surfaces the mineral often stands out in knob-like square-shaped or rectangular excrescences coated with a pale dirty yellowish-brown crust of decomposition-products; now and then the crystals are up to half a square inch in area. On fresh fractures the mineral appears as large pale pinkish-gray blebs. It is much less plentiful than cordierite, but in many outcrops several andalusite-individuals — sometimes more than ten — fall within the limits of an ordinary handspecimen. The mineral is often scattered irregularly, but may become more plentiful along bedding-planes; it was not found in any of those rocks which originated as ferruginous and siliceous sediments, and no doubt a thoroughly argillaceous material is, — as

1) W. C. Brögger, **9** and A. L. Hall, **31**.

in the case of its invariable associate cordierite — essential for its formation.

In thin sections andalusite forms large plates (Pl. XXVII, fig. 3, Pl. XXVIII, fig. 2, Pl. XXX, fig. 3) with a characteristic high relief, a cloudy appearance and often passing outwards into a narrow irregular clear border. The edge of the crystals is often highly but minutely indented (Pl. XXIX, fig. 1) like most of the other contact-minerals are. Inclusions comprise quartz occasionally a little biotite and garnet.

Hornblende. This mineral has a limited distribution but is very often abundant in the more strongly ferruginous horizons; thus it is highly characteristic of many outcrops belonging to the Water Tower Slates and similar ferruginous bands in the Government Reef Series, e.g. on Rietpoort, Witbank, Koedoeslaagte, etc. In the field the mineral often shows up as scattered dirty yellowish radiating tufts of needles in the form of rosettes up to a quarter of an inch in diameter. Good examples were observed on Leeuwdoorns on Rietpoort a little east of the Potchefstroom road, and on Witbank west of the school house; these clusters are either irregular in their distribution or arranged in rudely linear fashion.

In thin sections the amphibole is nearly always accompanied by much magnetite in minute grains or by garnet (Pl. XXIV, fig. 2), and occurs in an acicular habit or in somewhat broad needles. These are often bunched together and terminate in both directions in a divergent aggregate so as to resemble sheaves of corn (Pl. XXX, fig. 4); in places they form rosette-like aggregates (Pl. XXVI, fig. 2) or fan-like groups of extremely delicate curvilinear and colourless needles. The mineral is usually pale yellowish-green, greenish-yellow, or almost colourless. Not infrequently it is distinctly green or bright green, with a very faint bluish tinge, such variations being sometimes displayed within a single sheaf. All the observed amphibole is monoclinic and probably represents at least two varieties. The bright green pleochroic type is less common and belongs to the actinolite group; the faintly coloured or nearly colourless kind is most likely an amphibole low in alumina and rich in iron, allied to the grunerite group (Pl. XXVII, fig. 1). The rocks characterised by these hornblendes are essentially banded ironstones, comparable to similar rocks in the Pretoria or Lower Griqua Town Series; here ferrous silicate hornblende is also abundant and with microscopic characters closely resembling those of the amphiboles in the altered ferruginous bands in the Vredefort Mountain Land.

Felspars. In a few thin sections of the altered argillaceous rocks small irregular grains are found with definite albite twin-lamellation showing very low extinction. With higher power and in convergent light grains can now and then be observed which are biaxial but without twin-lamellae; such grains are probably also plagioclase. Potash felspar was only identifiable in a very few instances.

Staurolite. This mineral has been mentioned as occurring in the Zijferfontein area east of Parijs by PENNY [1]) but the authors only found it in a hornfels of the Government Reef Series close to the alkali-granite on Koedoeslaagte north-west of Parijs; in hand-specimens the mineral could not be detected. Under the microscope it forms fairly plentiful pale golden-yellow irregular crystals with high relief and the characteristic pleochroism; the outlines are again thoroughly indented.

Tourmaline. In most of the highly altered rocks with much cordierite and belonging to the Hospital Hill Slates e.g. on Witbank, tourmaline was found in thin sections, though never plentifully. It cannot be detected in handspecimens, and was not observed in other horizons. The mineral nearly always forms minute inclusions in cordierite in very small rounded grains and tiny laths; since it is invariably accompanied by much brown mica, it is liable to be overlooked. The identity is based on the rhombohedral outlines of the rounded grains, the position of maximum absorption of the laths (contrary to that of biotite) and on the colour, which is a distinct greenish-brown as compared with the bright pure reddish-brown of the mica. It is not possible to decide definitely in favour of its detrital or metamorphic origin, but the close restriction of the mineral to cordierite suggests the latter mode.

Sillimanite. This mineral is very rare, having only been observed in the altered quartzites on Koedoeslaagte close to the margin of the alkali granite-intrusion on that farm, and in the hornfels of the Jeppestown slates. Its presence was only established microscopically, as an alteration product of biotite, the margins of which are frayed out into tufts, curved strands, or whisps of sillimanite-needles of almost hair-like delicacy (Pl. XXVI, fig. 3).

3. *Microstructure.*

The altered rocks are remarkably fresh and always holocrystalline. This complete crystallisation is highly characteristic of rocks which have undergone the highest degree of metamorphism, as e.g. those found in the inner contact zone of the Bushveld Igneous Complex [2]) or in the Christiania Region [3]).

G r a n u l i t i c S t r u c t u r e is pronounced and widespread, generally uniform throughout the section; the less intensely the rocks have been altered the finer is the "granularity" and the more highly they are altered — specially when large contact-minerals are present — the more is the fineness of grain subject to rapid and pronounced variation. In general, however, the rule holds good — more so with the altered shales and banded ironstones than with the quartzite — that the coarseness of grain is proportional to the intensity of the metamorphism. This comes out very

1) F. W. PENNY, 66, p. 330. The authors observed abundant garnet and amphibole in this ferruginous hornfels, but failed to find any staurolite.

2) A. L. HALL, 27 and 28.

3) V. M. GOLDSCHMIDT, 23.

well, for example, when comparing the evenly fine-grained bands of biotite-hornfels sometimes intercalated in the main Hospital Hill quartzite (Waterpoortje [1]) near Leeuwdoorns) with the very coarse andalusite-slates on Witbank etc.

Pavement structure is very common in some of the altered quartzites, or —in case of metamorphosed shales — in the irregular patches of recrystallised groundmass which consist of many almost uniform grains of quartz in direct contact with one another and without any cementing matrix. This is practically identical with a "mosaic".

Cataclastic structure is very marked along flinty crush-rocks, specially in some of the quartzites, and leads to stringers or patches of finely granular quartz-mosaic, sometimes arranged like a wreath round larger crystals of quartz (Pl. XXII, fig. 2 and 3). It is remarkable that although the whole succession has subjected to great pressure, there is very little evidence of shearing movement.

Sieve-structure with highly irregularly but minutely indented outlines of the mineral concerned, is also abundant, specially in the large crystals. It is characteristic of biotite, garnet, cordierite, andalusite and to a minor extent of ottrelite and staurolite, and is due to inclusions which are not infrequently so plentiful as to occupy a combined area greater than that of their host.

In establishing the order of crystallisation the criterion of inclusions is helpful, and it is on this principle that Table I is mainly

TABLE I. MINERALS OF THE METAMORPHIC ROCKS.

A. Original.	B. Metamorphic (in order of crystallisation).	C. Alteration Products.
Magnetite Zircon Quartz (of quartzites, banded siliceous iron-stones etc.).	Quartz (in recrystallised shales etc.) Garnet (Biotite, Ottrelite, Hornblende, Tourmaline, Staurolite, Cordierite, Andalusite, Hypersthene).	Chlorite. Sillimanite ? Hydrated Iron Ore.

based; the latter also gives the classification of the minerals according to origin [2]). The data are not so complete as could be desired, though over 120 thin sections were examined; some uncertainty exists in case of the minerals bracketed in column B since they were not always observed as inclusions of one in the other. In general, however, the order of crystallisation among the minerals in column B is such that anyone is liable to carry inclusions of any others above, but not one below, it, within that column. It is also uncertain whether the quartz of column A should be regarded as strictly original, or whether it should not be classed as

1) Waterpoortje is a portion of the farm Rhenosterpoort 504.

2) Muscovite and felspar have been ignored.

metamorphic, since the quartz-grains (though chemically unaltered) have been recrystallised. The criterion used in filling column B has been to assign to it only the results of the rearrangement of original material into minerals not found in the unaltered rocks.

4. *The Principal Types of Metamorphic Rocks.*

Most of the altered rocks belong to one or other of the three main groups shown in Table II, which takes no account of local and minor intermediate phases like sandy flagstones etc. Many occurrences of hornfels, notably among the argillaceous rocks correspond to Class I of the classification given by GOLDSCHMIDT for the Christiania contact-belt [1]).

TABLE II. VARITIES OF METAMORPHIC ROCKS.

A. Highly Siliceous Rocks.	B. Highly Ferruginous Rocks.	C. Argillaceous Rocks.
Pure Quartzites (recrystallised quartz) *Impure Quartzites* (recrystallised quartz, garnet, very rarely biotite) e.g. Orange Grove Quartzite — pure. Hospital Hill Quartzite (locally) — impure.	*Ferruginous Siliceous Rocks* (recrystallised into quartz, garnet, hornblende, magnetite, very rarely biotite). e.g. Water Tower Slate.	*Dark Crystalline Hornfels* in many varities (recrystallised into quartz, biotite, cordierite, andalusite, ottrelite, garnet, staurolite, tourmaline). e.g. Hospital Hill Slate, Jeppestown Slate, etc.

a. Highly Siliceous Rocks. These include all the altered quartzites, both pure and impure, though as a rule no difference between these varieties is noticeable in handspecimens.

The pure altered quartzites are white or dirty yellowish-white evenly medium-grained rocks consisting almost wholly of quartz with highly indented and interlocking outlines (Pl. XXVII, fig. 2); in addition one may find very occasionally a few minute specks of some micaceous mineral. On Kopjeskraal not far from the basal Orange Grove Quartzite the authors found an extremely coarse somewhat glassy quartzite comparable to those remarkably coarse-grained rocks included in the highest layers of the Magaliesberg Quartzite within the inner contact-belt of the Bushveld Complex, or found as large xenoliths in the norite itself — and recently described as the Doornpoort-type [2]).

The impure altered quartzites form narrow bands in the succession of similar but pure rocks from which they only differ by being somewhat darker in colour. In the main Hospital Hill Quartzite on Witbank such a band consists of interlocking grains of quartz with much garnet in small

1) V. M. GOLDSCHMIDT, 23.

2) A. L. HALL and A. L. DU TOIT, **30**, p. 75.

rounded crystals (in part faintly anisotropic). Another good example belongs to the Main-Bird Quartzite on Koedoeslaagte (near the northern edge of the alkali-granite intrusion), where the rocks contains a little biotite passing into sillimanite. Other varieties are occasionally found as narrow sandy layers or washes, often only a few inches thick interbedded with slates, and are referred to below.

b. Highly Ferruginous Rocks. The second group is typically represented by the Water Tower Slates in the Hospital Hill Series, and by similar rocks e.g. in the Government Reef Series on Koedoeslaagte in contact with an alkali-granite intrusion.

Garnet-amphibole-hornfels with magnetite. One phase consists of heavy almost black highly ferruginous fine-grained rocks not unlike coarsely banded ironstone with scattered garnet and tufts of yellowish brown amphibole needles. Their mineral content in order of abundance is given by : quartz, magnetite, amphibole, garnet (Pl. XXIX, fig. 4, Pl. XXX, fig. 4).

A second phase consists of evenly medium-grained pale grayish-violet rocks with abundant garnet (Pl. XXX, fig. 2) in rather large pinkish more or less evenly scattered crystals. They are distinctly less ferruginous than the normal Water Tower Slates and form good outcrops on Brakfontein near the foot of a conspicuous gabbro-kop overlooking the Vaal River, and in the bed of that stream near Baviaanspoort a little below the main Hospital Hill Quartzite at a little waterfall (Pl. XXIX, fig. 3). Their composition is practically as before, but the minerals show this order of abundance : quartz, garnet, amphibole, magnetite.

c. Argillaceous Rocks. This is the most abundant group, the metamorphism often producing very striking rocks owing to the abundance of conspicuous contact-minerals — specially on weathered surfaces — over continuous outcrops several hundred feet thick. Local variation in the purity of the original shaly material leads to a corresponding latitude in the character and relative abundance of constituent minerals. The following grouping enumerates only the principal varieties between which there are a good many transitions: Their mineralogical composition and microstructures show many analogies with the hornfels of class I, as defined by Goldschmidt in the Christiania region [1]).

Biotite-Hornfels. These are evenly fine-grained dark coloured glistening rocks which consist of abundant biotite and quartz in approximately equal dimensions. None of the other contact-minerals are present, except very rarely some andalusite or cordierite in minute amounts. Such rocks are comparatively rare ; good examples are found in higher horizons of the Government Reef Series, e.g. in the Koedoeslaagte area or in xenoliths of the Jeppestown Slates up in the alkali-granite of Schurvedraai.

Staurolite-Biotite-Hornfels. This type is very restricted

1) V. M. GOLDSCHMIDT, **23**, p. 140.

and was only found round the southerly of the two alkali-granites on Koedoeslaagte. It is a uniformly medium-grained dark coloured rock with this essential composition : Biotite, quartz, staurolite.

Cordierite-Biotite-Hornfels (Pl. XXIX, fig. 2, Pl. XXVI, fig. 1, Pl. XXVIII, fig. 1) without andalusite, but with or without garnet; the presence of the last mineral leads to the variation: cordierite-biotite-garnet-hornfels (Pl. XXV, fig. 2). These rocks — together with the next type — are the commonest varieties of altered shales often assuming a very great thickness. They are eminently characteristic of the Hospital Hill Slate horizon. The finest outcrops occur on Rietpoort, on Kopjeskraal, on the adjoining farm Witbank and on Leeuwdoorns west of the main road leading from Vredefort to Reitzburg.

The weathered rusty brown surfaces are freely pitted by oval depressions due to cordierite (as explained above) ; on fresh fractures this hornfels is a thoroughly dark (almost black) holocrystalline rock, with a characteristic glittering appearance owing to much biotite, mostly in tiny flakes. The texture is uniformly medium- or occasionally coarse-grained with little mineralogical differentiation apart from mica, though cordierite can sometimes be detected in large faintly outlined oval or rounded areas. The bedding-planes are usually obscure in handspecimens, emphasized by the linear arrangement of certain constituents, but in larger outcrops the original stratification is well marked. Metamorphism has transformed what must have been more or less finely laminated slate or shale into hard thickly bedded hornfels; locally the almost massive character is shown by a tendency to spheroidal or discoidal weathering, so that one can sometimes prize off from a large block a curved slab, — much like in the case of hummocky outcrops of "ball" granite. Here once more is a close point of contact with the behaviour of massive hornfels-outcrops from the aureole of the Bushveld Complex in the north-eastern Transvaal.

The intense induration and consequent massive character is also shown by a tendency to conchoidal fracture and to emit a metallic ring when thinner slabs are struck a violent blow with a hammer.

The close association of cordierite-biotite-hornfels with andalusite-hornfels is often shown in successions of alternating bands from a few inches up to a few feet thick, of these two types e.g. above and below the Lower Hospital Hill Quartzite on Witbank.

The constituents of the cordierite-biotite-hornfels varieties are these: biotite, cordierite and quartz as essentials but often accompanied by ottrelite, with garnet and tourmaline as accessories.

Andalusite-cordierite-biotite-hornfels. This variety (Pl. XXVII, fig. 3 ; Pl. XXVIII, fig. 2 ; Pl. XXIX, fig. 1 ; Pl. XXX, fig. 3; Pl. XXXI, fig. 3) contains andalusite [1]) as the most characteristic mineral,

1) MOLENGRAAFF (**58**, p. 198), in 1894, erroneously reported the occurrence of corundum in this hornfels; later examination has proved beyond doubt that the rock does not contain any corundum.

but the latter is less plentiful than cordierite ; if garnet is also present, the rock may be designated as g a r n e t - a n d a l u s i t e - h o r n f e l s. Andalusite is always accompanied by cordierite, but the converse does not necessarily hold good. These rocks are most striking in the field, since the leading mineral nearly always stands out from weathered surfaces in conspicuous knobs as explained above. Such hornfels is apparently restricted to the Hospital Hill Series (Hospital Hill Slate), but it includes the horizon directly above the Upper Hospital Hill Quartzite. They are hard, holocrystalline and very coarse black rocks ; fresh surfaces are very similar to those of the cordierite-biotite-hornfels just described, except for the conspicuous blebs of andalusite. Many of the field appearances and other features of the cordierite-hornfels group also hold good for the andalusite-bearing rocks, which are very closely associated with the former in which they form layers. Andalusite may be irregularly scattered or help to express planes of bedding by its orderly distribution.

The composition is identical with that of the preceding variety, except that the essential minerals include andalusite.

d. Intermediate Siliceous-Argillaceous Rocks. These are of minor importance, since they only form thin bands in the argillaceous phases. They are well exposed in a little knoll on Brakfontein and can also be seen in the hornfels close to the Lower Hospital Hill Quartzite on Witbank ; they appear in the field as lighter coloured very fine-grained quartzitic looking bands and have a composition intermediate between that of groups *a* and *c*, namely : Quartz, biotite, garnet.

B. The Metamorphism of the Igneous Rocks.

The igneous rocks which represent contemporaneous basic lava-flows intercalated in the girdle of sediments round the Vredefort Granite must have undergone the same metamorphism as those sediments themselves.

The agents of metamorphism were pressure, the effects of which are found in abundance, both in the Vredefort Granite and in the encircling sediments, and heat, by the influence of which the rocks of the Lower Witwatersrand Beds now show a most intense thermal metamorphism, as described above in the first portion of this chapter. Thus one may expect to find in the contemporaneous igneous rocks the effects both of dynamic and of thermal metamorphism. In the following pages it will be proved that indeed these igneous rocks are highly altered, but that it is not feasible to distinguish which portion of the metamorphism is the result of pressure and which of heat.

Among the contemporaneous igneous rocks in the Lower Witwatersrand Beds the thick belt at the base of this system, known as the B a s a l A m y g d a l o i d, ranks first in importance and the alteration of the rocks of this belt only will be described now, because the other basic effusives show the same character of metamorphism. On page 25 it has already been pointed out that this belt before its metamorphism most probably consisted of a complex of basic lavaflows composed of amygdaloidal diabase. This rock originally was probably medium- to fine-grained, and fairly rich in amygdules, which are, however, unevenly distributed ; it must have been composed chiefly of basic plagioclase, augite and some ilmenite, and must have possessed the diabase-structure typical of such rocks.

The Basal Amygdaloid is now profoundly altered, but macroscopically it still has the aspect of a diabasic amygdaloidal rock (Pl. II, fig. 2). Seen with a strong pocket-lens, numerous small needles of green amphibole are visible. Only the microscope reveals how profound the metamorphism has been.

Under the microscope the rock is rather uniform in composition wherever it occurs. It is entirely epidioritised and chiefly made up of quite fresh small phenocrysts of actinolitic amphibole and a granular groundmass ; as it is now the rock might be called a hornblende-granulite.

The amphibole occurs as slender prisms, showing the pleochroism common in actinolite :

𝔞 — pale yellowish-green to pale straw-colour,
𝔟 — green to pale green,
𝔠 — green and pale green to bluish-green and pale blue.

Now the crystals of amphibole are closely packed and only leave little room for the groundmass, then again the structure is more open, the amphibole-prisms being in places wider apart. Not rarely a kind of felt or mat is formed, the slender prisms lying with their longer axes prevailingly in two directions, more or less at right angles.

Besides amphibole also apatite and titanite occur as phenocrysts ; the apatite in short prisms, the titanite in lumps of rather irregular shape. Both these minerals, however, are confined to the amygdules or their near vicinity.

The groundmass consists as a rule chiefly of two or three minerals in small grains. One of these is perfectly colourless and pellucid and shows all the properties of quartz, the others are slightly less transparent as compared with the quartz, and have a distinctly higher index of refraction ; these latter not seldom develop a kind of sieve-structure and then enclose grains of quartz. In many places one of the latter minerals show twin-lamellae and can with certainty be recognised as a basic plagioclase belonging to the bytownite-anorthite group, both systems of lamellae very often getting dark simultaneously at an angle of extinction of 45°. In some of the slides a considerable portion of the groundmass can thus be made out to be composed of a very basic felspar, but in several others of these latter minerals twin-lamellae are very rare or could not be found at all. In some slides it could be made out with certainty that cordierite occurs as the third component in the groundmass, then being distinguishable from the quartz by its slightly higher index of refraction, its well-developed sieve-structure and by a peculiar gathering of small dark inclusions near the central parts of the grains, which is absent in the crystals of quartz. Cordierite, however, may be present at some places in larger quantities than could be made out with certainty, and then it probably plays a not unimportant role in the composition of the granular groundmass. Zoisite is found in varying, often considerable quantities as lumps or as not well-defined often honey-combed prisms ; biotite, enveloping zircon, and calcite are found in some of the slides. Minute grains of ilmenite are disseminated through the rock when titanite is rare or absent ; in other instances the ore is entirely absent but then small specks of titanite are scattered in the rock ; evidently the sphene has been formed at the cost of the original ilmenite.

The occurrence of cordierite in the Basal Amygdaloid deserves special attention.

In Chapter III 3, b mention is made of highly metamorphosed sediments which, as isolated blocks, are found in some places in a certain horizon in the Basal Amygdaloid. It is only close to such blocks that cordierite is found in abundance in the Basal Amygdaloid. These blocks of highly altered sediments carry actinolitic amphibole, garnet, quartz and cordierite as their chief components. The metamorphosed Basal Amygdaloid near by contains much cordierite in the groundmass and sometimes in the amygdules, as small crystals with marked sieve-structure and numerous inclusions. In one spot the Basal Amygdaloid proved to be converted into a medium-grained rock, composed of large prisms of actinolitic hornblende and a mosaic of interlocked good-sized crystals of perfectly fresh cordierite, almost devoid of inclusions and showing sieve-structure moderately developed. It appears that during the process of metamorphism and recrystallisation of the Basal Amygdaloid and the blocks of altered sediments chemical reactions between the two rocks took place, by which alumina has been taken up from the altered shaly sediments, which attributed to the growth of crystals of cordierite in the epidioritised Basal Amygdaloid.

The amygdules in the metamorphosed rock are evidently recrystallised in a complicated and variable manner, and now show a texture and a mineralogical composition rather different from those usually found in amygdules of basic rocks.

The following *types of amygdules*, which are connected by numerous transition phases, were observed :

First type. The amygdule is not well defined and is nothing but a more open space in the rock, in which the minerals of the groundmass, especially quartz, are crystallised in larger individuals than at other places (Pl. XXXII, fig. 1). Prisms of actinolite always protrude into these amygdules from the surrounding denser parts of the rock (Pl. XXXII, fig. 2 and 3). No definite rim is present around such amygdules [1]). This type is very common.

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1) Sometimes a rim is faintly indicated around these amygdules, the crystals of amphibole there being somewhat more crowded.

Second type. This is distinguished from the first by the fact, that besides actinolite, quartz, and plagioclase, also other minerals such as apatite and titanite take part in the composition of the amygdule (Pl. XXXIII, fig. 1 and 2). The amygdules of this type have no concentric structure just as in the first type, but faint exterior rims made up of actinolite and titanite are sometimes developed.

Third type. Here the amygdules are rimmed and consequently show a more or less concentric arrangement of their constituent minerals. These rims may belong to the groundmass round the amygdules, or may form part of the latter themselves. The first kind we shall call an exterior rim, the second an interior rim.

Subtype a. Interior rim only. The rim is the marginal portion of the amygdule itself and is composed of the same minerals as the central portion. In the rim, however, these are fine-grained, whereas in the kernel a coarse mosaic is formed (Pl. XXXIII, fig. 3). Quartz is usually the predominant mineral in these rims.

The actinolite within the amygdules is often concentrated more or less between the kernel and the rim, thus emphasizing the concentric arrangement. Figures 1 and 2 on Pl. XXXI show the actinolite strongly concentrated in an almost closed zone or ring between the outer fine-grained quartz-envelope and the kernel, which consists of one single crystal of quartz. At the spot, where the ring of actinolite is not closed two fairly large crystals of zoisite with well marked sieve-structure occur.

Subtype b. Both rims, or exterior rim only, developed. The exterior rim is almost, or nearly free from femic minerals (Pl. XXXIV and XXXV, fig. 1), and it appears as if here the femic substances had been extracted from the groundmass and been concentrated in the wholly recrystallised amygdule [1]). The bulk of the exterior rim consists in the first place of two minerals which are always present in the groundmass viz. quartz and basic plagioclase, the latter with an index of refraction perceptibly higher than that of quartz, and sometimes with an indication of sieve-structure, when grains of quartz are enclosed. Besides quartz and plagioclase, zoisite is found in smaller and larger crystals, often with sieve-structure, not seldom in abundance ; further apatite here and there in plump often rounded prisms and probably cordierite in patches, with a strongly marked sieve-structure, but without well-defined crystal-outlines. The line of demarcation between this exterior rim and the amygdules is pretty sharp, but away from the latter the rim merges gradually into the groundmass of the rock.

The kernel of the amygdules generally consists of one simple crystal of quartz enclosing other minerals, often in great quantity. In the amygdules shown on Pl. XXXV such a quartz-kernel encloses actinolite only, but in

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1) The amygdules originally were probably composed of quartz and during the process of recrystallisation have extracted femic substances from the surrounding basic rock, which were used to build up femic silicates in the amygdule.

those shown on Pl. XXXIV the central crystal of quartz encloses apatite, iron-ore and actinolite. Sometimes a large central crystal of quartz is enveloped by a zone composed of actinolite in a few large crystals, which poikilitically embrace quartz and cordierite, around which follows the exterior rim devoid of femic minerals, which finally more or less gradually passes into the groundmass of the rock.

The metamorphosed Basal Amygdaloid shows the effect of strong pressure in many places also by crush-zones and crush-lines, which traverse both the mass of the rock and its amygdules. Mylonites are found in these crush-zones and in places these are extremely fine-grained and then pass into flinty crush-rocks, referred to in chapter III, section 8.

The Basal Amygdaloid, which in the way described above is altered into a rock here named hornblende-granulite, shows the effect of pressure and heat. This formation is epidioritised and it thus shows the characteristics which are so well exemplified in the epidiorites described in Chapter III, Section 7, the same minerals being much in evidence which also typify the epidiorites: actinolite, titanite and zoisite. The total absence of albite in our granulite may be accounted for by the very basic composition of the plagioclase of the original diabasic rock. The authors believe that the process of epidioritisation has been caused in the Basal Amygdaloid chiefly, if not exclusively, by pressure, just as in the other epidioritised rocks of the area.

The hornblende-granulite, however, differs in not unimportant points from ordinary epidiorites ; the amygdules have been recrystallised in a way, which perhaps can better be explained by the effects of thermal than of dynamic agencies. The origin of the most perfect granular structure of the groundmass may be due both to dynamic and thermal influences. The development of rims of fine-grained minerals round the amygdules and the mosaic-structure often found in them may be due to pressure, whereas the poikilitic and sieve-structures may have been caused by thermal agencies.

Concluding, the authors believe that both pressure and heat had their share in causing the intense metamorphism to which the Basal Amygdaloid has been subjected.

C. The Causes of the Metamorphism.

The occurrence of metamorphic rocks all round the central granite at once raises the question whether they may not be due to an intrusive relationship between the granite and its encircling sediments.

The writers regard the Vredefort Granite as belonging to the "Older" type, and since the formations surrounding it belong to the Lower Witwatersrand System, their metamorphism cannot be due to this "Older" granite, which is now agreed to be earlier in age than those sediments.

Quite apart from this conclusion, however, there are several features pointing to a non-intrusive relationship.

Assuming that the age of the Vredefort Granite is younger than that of the Lower Witwatersrand rocks, as concluded by several writers, then the scale of its metamorphism must bear some reasonable proportion to the extent of the granite. The latter forms a circular area 40 km. (25 miles) in diameter, and, if intrusive, should lead to an aureole arranged like an annular belt surrounding the periphery; since the contact-belt has a maximum width of not less than 4 miles (6.4 km.), it follows that the surface-element of the agent to that of its effect is as 156 is to 116. These figures indicate a ratio between cause and effect out of all reasonable proportion and imply a stupendous source of energy; hence this line of reasoning leads to the same conclusion that the metamorphism is not due to the central granite.

Further, on the same assumption, the effects of intrusion of the granite should be more or less symmetrically distributed, should show a progressive decrease in intensity from the granite-periphery in all directions outwards, and should lead everywhere to metamorphic rocks characteristic of contact or thermal metamorphism, i.e. of that depending essentially on a large intrusion. These conditions are not satisfied, however, as will appear below.

The Vredefort Granite retains its leading characters right up to its contact with the Basal Amygdaloid or with the lowermost Orange Grove Quartzite. It shows no fine-grained selvages and remains as coarse-grained as it is well inside its mass. The field-relations are not at all like those of a younger granite intruded into sediments, against which it would show chill-phenomena or a more basic marginal phase [1]). Hence the absence of endomorphic phenomena further negatives an intrusive relationship of the Vredefort Granite to its girdle of sediments.

No case of a granitic apophysis into the surrounding rocks of the Lower Witwatersrand System has so far been observed. Since they are an almost invariable feature of the relationship between an intrusive body and its associated older rocks, their absence in the Vredefort Mountain Land is not without significance, when taken in conjunction with other arguments, notwithstanding the negative character of this evidence.

The small area embracing portions of the farms Tweefontein, Vergenoeg and Zijferfontein some 13 km. east of Parijs, was made the subject of a detailed study by PENNY [2]) who came to the conclusion that the Vredefort Granite is intrusive into the Witwatersrand sediments, the stratigraphical difficulty being removed by his suggestion that the "granite is, if not "contemporaneous with, at least connected with the same epoch of igneous "activity as, the Red Granite of the Northern Transvaal".

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1) It should be recalled that the basic marginal intrusions within the granite (discussed in Chapter III, 7a) are certainly not differentiation-products of the latter.

2) F. W. PENNY, **66**.

This conclusion is based upon the metamorphism of the slates, upon a little intrusion of granite in the middle of the diabase, and upon a small tongue of granite penetrating the sediments. The metamorphism of the slates certainly exists, but on the other two points the writers come to a different conclusion.

The little intrusion of granite is shown on the map accompanying PENNY's paper and appears in his section [1]) as intrusive into diabase, but it is not an intrusion at all, only a circumdenuded outlier of granite resting on a sill-like intrusion of basic rocks ; these pass with a low dip under the former.

The small tongue of granite penetrating the sediments [2]) has a distribution which is difficult to reconcile with a relationship other than intrusive. The rock is clearly abnormal and has become hybridised through reaction of acid and basic magmas — as pointed out by PENNY — but the writers find that this little tongue is not an apophysis of the Vredefort Granite hybridised by the assimilation of basic material, but on the contrary, an intrusion of a gabbroidal magma into the Vredefort Granite and the lowermost portion of the Witwatersrand Beds, and modified by the assimilation mainly of granitic and quartzitic elements (p. 37 and fig. 7). Hence it is not an offshoot of the main granite-mass but is later in age, so that it does not afford any evidence for the intrusive character of the Vredefort Granite.

It is therefore concluded that the *Vredefort Granite is not intrusive* into its girdle of Witwatersrand Beds, and hence has not caused their metamorphism ; being therefore earlier in age than the Witwatersrand System, that granite belongs to the "Older" group, so that the accepted non-intrusive relationship of the latter towards that system holds good for the Vredefort Mountain Land also.

Yet metamorphic rocks do occur all round the Vredefort Granite ; what, then, is their metamorphism due to ?

The authors have come to the conclusion that the Vredefort Mountain Land presents a case of Polymetamorphism or Superposed Metamorphism in the sense in which these terms were first used by the writers referred to at the beginning of this chapter. It is concluded, that this principle has operated in the form of two components in succession — an earlier or dominantly a pressure-component, and a later or dominantly a thermal component ; besides a time-order, each component also had its space-order. It is emphasized, however, that in neither component has the agent been pressure alone or heat alone, but both of them cooperated, though in variable proportions. To fix ideas, the two contributing factors will be referred to as the Regional and the Local Component.

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1) F. W. PENNY, 66, map and Fig. 1.

2) This tongue is shown on Penny's map and also on its simplified copy in Fig. 8 on page 46 of this paper, in the left corner below.

1. The Regional Component.

This operated during the earlier stages in the metamorphic history of the Mountain Land, and pressure is its dominant agent, but not without the cooperation of heat. The emplacement of a major intrusion is not involved, and consequently the effects are not those that lead to what is generally understood by contact-rocks.

To this component must probably be attributed the occurrence all round the granite of the very common garnet-amphibole-hornfels derived from the ferruginous Water Tower Slates and the conversion of the lavas of the Basal Amygdaloid into hornblende-granulite.

An intensive study of GOLDSCHMIDT's great classic on the metamorphic phenomena of the Christiania region — already alluded to — has indicated to the authors many instructive analogies with the Vredefort Mountain Land, e.g. in the varieties of hornfels, but differences — equally instructive — have also been noted. Thus pyroxenes, both monoclinic and rhombic, are characteristic of several classes of hornfels in the Norwegian metamorphic province; this is not the case in the Vredefort Mountain Land, where amphibole is abundant, e.g. in the Basal Amygdaloid and Water Tower Slates — exactly those types of metamorphism which are constant all round the granite. GOLDSCHMIDT argues that with a combination of very high pressure and fairly high temperature pyroxene cannot be formed, but that amphibole is a typical high-pressure mineral. This argument applies specially to the Basal Amygdaloid (hornblende-granulite) because in the complete absence of any evidence of the assimilation of foreign matter its bulk-analysis (given above) more or less represents the composition of the original material. The latter is sufficiently complex to have allowed a fair range of molecular rearrangement to enable pressure and temperature to have full play in guiding the mineral association resulting from metamorphism. On the other hand, the ferruginous Water Tower Slates have a much simpler composition, since they consisted mainly of quartz and magnetite, which predisposes them to the development of ferrous silicate hornblende under metamorphism.

The probable existence in the Vredefort Mountain Land of a regional component of polymetamorphism also finds some support from the standpoint of the law of volumes [1]). Great pressure tends (generally) to cause the formation of those minerals, the molecular volume of which is less than that of its constituent oxides. To that group belong garnet, staurolite and ottrelite. The first is extremely abundant all round the Vredefort Granite, and staurolite is also occasionally observed.

The abundance of ottrelite in the hornfels of the Lower Witwatersrand System has been shown in Section *A* of this Chapter, so that here also one might argue in favour of its high pressure origin in conjunction with the

1) F. BECKE, 5. The law of volumes is clearly traceable in the metamorphic province of the Bushveld Complex. (A. L. HALL, 27, pp. 19—20).

law of volumes. Yet ottrelite occupies a special position among metamorphic minerals; since the works of RENARD and GOSSELET on the Ardennes it has been for many years regarded as characteristic of "dynamic" metamorphism; others e.g. WEINSCHENK [1]), maintain that it specially characterizes contact-metamorphism under great pressure. Within the aureole of the Bushveld Complex ottrelite occurs in the Western Transvaal [2]) under conditions excluding all possibility of regional metamorphism. Even among the altered Lower Witwatersrand rocks in the Vredefort Mountain Land its distribution is not that which would be expected from a regional factor, but is very intimately associated with, and practically confined to that of, cordierite. For these reasons the authors do not regard this mineral as having a diagnostic value definite enough to justify wider conclusions.

While it is clear therefore that great pressure has operated, there is little evidence of shearing or other movement; it should be remembered that the sericite-schists (Orange Grove Quartzite) are very restricted in their distribution. It is doubtful, at the same time, whether such a change as the conversion of the Basal Amygdaloid into hornblende-granulite could have been accomplished without the influence of heat, and the cooperation of fairly high temperature in addition to the dominant pressure-factor, most likely existed. This raises the question of the conditions which gave rise to what is here called the regional component.

The Causes of the Regional Component. Two causes suggest themselves. In the first the development of pressure is anterior to updoming and due principally to load, i.e. to the weight of superincumbent formations, orogenic forces being excluded or allowed only a minor part. In the second the development of pressure is due mainly to orogenic forces (generated during updoming), though load may have had a minor contributary share.

In connection with the *first suggestion*, there is no reasonable doubt that prior to the updoming of the central granite, the Ventersdorp and Transvaal Systems extended over what is now the Vredefort Mountain Land. The succession would then be as follows:

Pretoria Series	3600 m.	(12000 ft.)
Dolomite	1200 m.	(4000 ft.)
Black Reef Series	negligible.	
Ventersdorp System	1500 m.	(5000 ft.)
Upper Witwatersrand [3])	3600 m.	(12000 ft.)
Lower Witwatersrand [3])	3000 m.	(10000 ft.)
Total	12900 m.	(43000 ft.)

1) E. WEINSCHENK, **91**, p. 138.

2) A. L. HALL, **28**.

3) These values were supplied by Mr. L. T. NEL, M.Sc. and are based on his recent survey of the area under discussion (on the Transvaal side). KUNTZ, in the year 1903, estimated the thickness of the Upper Witwatersrand near Venterskroon at about 4400 m. **45**, p. 110).

Assuming the temperature gradient as 35 m. (118 feet) per degree centigrade the above total thickness would at the bottom of the succession correspond to a pressure of 3650 kg. per square cm. or approximately 3500 atmospheres, and to a temperature of nearly 385 degrees centigrade. These values are of course purely approximate, but they at any rate indicate agents of sufficient intensity to account for thoroughly holocrystalline and coarse metamorphic rocks. Such a phase of metamorphism answers to the *Belastungsmetamorphismus* of MILCH [1]), i.e. "Load Metamorphism"; it is static and not dependent upon movement of rock masses, i.e. not dynamic. In fig. 17 the thickness is shown of the block of strata which the authors take to be possibly metamorphised by this agency in the Vredefort area.

The s e c o n d s u g g e s t i o n attributes the generation of high pressure to those forces by which the updoming and consequent overtilting of the succession was brought about.

It is probable that some element of truth is to be found in each suggestion, and that the establishment of the regional component depends on a combination of factors drawn from both ideas.

The first suggestion is well compatible with what is found in the Johannesburg area. There the Lower Witwatersrand Beds are not metamorphosed and, as is shown in fig. 16, at Johannesburg they were never

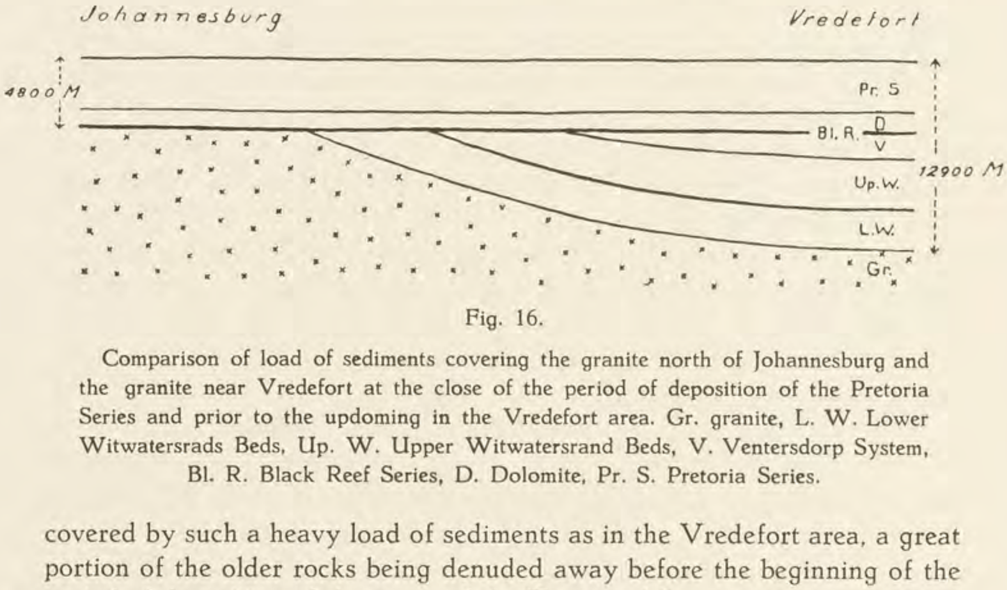

Fig. 16.

Comparison of load of sediments covering the granite north of Johannesburg and the granite near Vredefort at the close of the period of deposition of the Pretoria Series and prior to the updoming in the Vredefort area. Gr. granite, L. W. Lower Witwatersrads Beds, Up. W. Upper Witwatersrand Beds, V. Ventersdorp System, Bl. R. Black Reef Series, D. Dolomite, Pr. S. Pretoria Series.

covered by such a heavy load of sediments as in the Vredefort area, a great portion of the older rocks being denuded away before the beginning of the period of deposition of the strata of the Transvaal System.

In the Heidelberg area, on the contrary, according to ROGERS' survey, the Witwatersrand rocks appear to have been at one time buried under a weight of formations comparable to that found in the Vredefort Mountain Land as tabulated above. And yet there is certainly in this area nothing cor-

1) L. MILCH, **55** and **56**, p. 43.

responding to the garnet-amphibole-hornfels or other equally strong phenomena of pressure-metamorphism. It would appear as if in the Vredefort Mountain Land there was some special incident, and it is not excluded that the updoming of the Vredefort Granite supplied this incident. Its impetus (absent in the Heidelberg area) may have furnished that factor additional to load (common to both areas) which was perhaps necessary in order to turn the scale definitely in favour of a powerful regional component of pressure, capable of producing those coarsely crystalline metamorphic rocks which the load-factor alone could not develop.

The writers have been unable to discover definite evidence pointing unmistakably to one or the other suggestion, and have therefore presented both aspects, well aware that the nature of the case must introduce some speculative thought.

2. *The Local Component.*

This occupies a somewhat later stage in the metamorphic history of the region, most likely genetically connected with the updoming phase.

Over the central, eastern and western portions of the Mountain Land — that is along the circular area extending approximately from Leeuwdoorns, west of Vredefort, to Brakfontein (north-east of Parys) — there is a strong development of holocrystalline hornfels, of entirely recrystallised quartzite and of other metamorphic varieties, among which cordierite-hornfels and andalusite-hornfels are the leading types (see Sections on Pl. IV). It is this phase of metamorphism that is held to be due primarily to the Local Component of polymetamorphism, i.e. that in which heat is the dominant factor, though pressure has probably cooperated to some extent.

The minerals of the altered rocks, specially the abundance of biotite, with a habit typical of that mineral when due to contact-metamorphism, also the abundance of cordierite and andalusite, show that the alteration is that which normally results from the intrusion of a large body of igneous rocks into a succession of sediments. The same conclusion follows from the pronounced sieve- and pavement-structures.

The striking resemblance between the dark cordierite-hornfels from this area and that found in the inner contact-belt of the Bushveld Complex has already been noted, and it would be impossible in a collection of specimens drawn from both areas to assign each example to its source, even with an intimate field-knowledge of both provinces. GOLDSCHMIDT himself alludes[1]) to the great similarity of the hornfels of his group I to the cordierite-hornfels (Groothoek type) from the Bushveld aureole.

The distribution of the altered rocks, when studied from the point of view of the intensity of their metamorphism, is also instructive.

On Bloemfontein, north-east of Parijs, there are soft practically unaltered

1) V. M. GOLDSCHMIDT, **23**, p. 153.

shales belonging to the Hospital Hill Series, though represented further towards the west on Rietpoort, Kopjeskraal, Witbank, etc. by holocrystalline cordierite-hornfels [1]). On Anna's Rust the Basal Amygdaloid is still altered into hornblende-granulite, but finer grained and less intensely altered than e.g. on Rietpoort and further west. This suggests that somewhere near Anna's Rust, the superposition of both components ceases, so that towards the south-east a finer-grained hornblende-granulite persists as the result of the Regional Component alone, while in the other direction towards Rietpoort the granulite becomes more coarse-grained owing to the superposed effect of the Local or Thermal Component. North-west of Parijs, specially from Rietpoort to Witbank, the cordierite-hornfels group reaches its maximum development, and from that neighbourhood towards the south-west some of the metamorphic minerals decrease in size, and a tendency to somewhat less intense effects is noticeable. Sago-structure, so typical of the Hospital Hill Quartzites, could not be traced in the sector of most highly altered rocks, but can be recognised further towards the south-west (e.g. on Deelfontein).

Since the alterations reach maximum intensity over the Witbank area, it is along that section that one would expect any orderly distribution of rocks affected in various degrees, to show itself best. In passing across the succession from the margin of the granite the great thickness of altered rocks composed of holocrystalline Water Tower and thoroughly coarse Hospital Hill Slates with their many large contact-minerals, leaves the impression of an inner zone of intense metamorphism, but the effects within the Government Reef Series do not correspond to an outer zone of feeble metamorphism, since one finds no chiastolite, spotted or similar slates — such as the outer aureole of the Bushveld Complex shows in such profusion [2]). It is true that the shales are much reduced in the Government Reef Series; when they do occur, however, they have passed into biotite-staurolite-hornfels, a rock corresponding more closely to the hornfels-group within the Hospital Hill Slates than to types characteristic of an outer contact-zone; this is shown on Koedoeslaagte, for example, or in the Jeppestown Slates. Apart from the prevalent arenaceous character of the Government Reef Series, not readily reflecting metamorphic influences, the problem is further complicated by the two intrusions of alkali-granite. No doubt these exert some influence on the rocks in contact with them, but their scale is out of proportion to the widely spread hornfels-group distributed at intervals from the main ridge of the Hospital Hill Quartzite to the Main Bird Quartzite some 5 km. across the succession.

1) This feature does not of course imply the continued absence of metamorphic rocks from that point south-east-wards or southwards, since the Regional Component remained effective all round; the unaltered shales referred to may have been situated far enough above the base of the Witwatersrand System to have come outside the influence of that component.

2) A. L. HALL, 27.

It is therefore concluded that some indication exists of a progressive increase in the intensity of the metamorphism, but in a direction along the strike or concentric with the periphery of the Vredefort Granite (instead of across the strike or radially) and with reference to an irregular focus situated underneath the Witbank area ; that the arrangement of the altered rocks of the Local Component is excentric with reference to the central circle of granite ; that within the focus a separation into zones of progressive intensity is not possible, since within the focal area the metamorphism has on the whole, the features of an inner contact zone.

The Causes of the Local Component. Since the existence of such a component (thermal metamorphism) is well established, and since, further, the Vredefort Granite has been shown to be non-intrusive, one suspects the presence of a younger body of intrusive rocks, whose function in the metamorphic history of the Mountain Land has not hitherto been recognized.

The little masses of alkali-granite described in Chapter III *7d* are most certainly intrusive into the girdle of sediments, but are probably the upper portion of a large mass continuous underground though to a large extent concealed.

Since the distribution of the main mass of this younger magma with its little offshoots is clearly excentric with reference to the Vredefort Granite circle, its effects should also show an excentric distribution. This appears to be the case as shown above.

On the other hand, the intensity-factor of metamorphism does not depend upon proximity to the alkali-granite outcrops, but field-work very strongly suggests, that this factor is determined by the vertical distance to the younger magmatic basin which is hidden from view but underlies a large part of the northern and western section of the Mountain Land.

To define the extent of this Hidden Magma is obviously very difficult, and impossible with any degree of accuracy, but the position of its visible offshoots and the distribution of the metamorphosed sediments point to an agent something like 380 square km. in minimum extent ; of this some 15 square km. are exposed in the form of the Tweefontein boss and the three alkali-granite bosses ; to regard the basic marginal rocks within and near the periphery of the granite as partial magmas from the same hidden source — according to the writers' standpoint — would add an appreciable area to these surface indications.

No data are available for estimating the depth at which the upper surface of the concealed magma would lie, but since the intensity of the metamorphism is comparable to that of the aureole round the Bushveld Complex, a vertical depth in the neighbourhood of some 900 m. would represent the extreme distance up to which analogous results could be expected. It is of course possible, and perhaps probable, that the actual depth is much less, but it is unlikely to be much in excess of the above estimate.

It is to this agency that the Local Component is, in the opinion of the writers, due.

3. *The Space Order of the components and their Superposition.*

It was stated in the beginning of this Chapter that polymetamorphism might imply areas which were exposed to both components in succession, thus possibly leading to an accentuation of the metamorphism. It is very difficult — frequently impossible — to trace corresponding distinctions in the altered rocks, but there are a few significant features suggestive of superposition ; figures 17 and 18 are purely diagrammatic and introduced to facilitate the discussion.

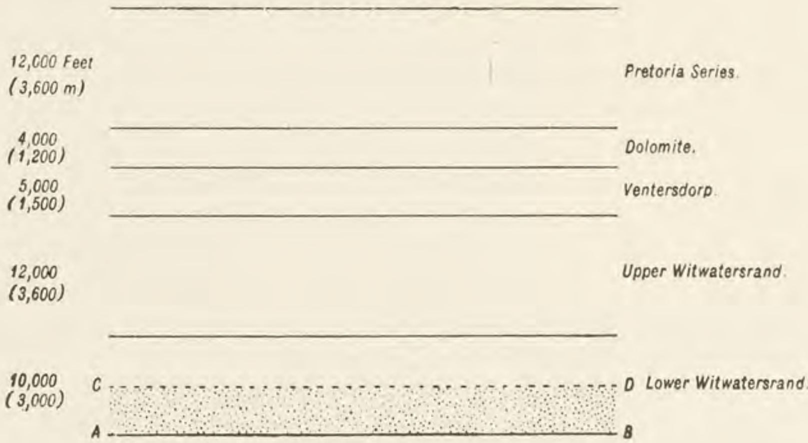

Fig. 17.

Ideal succession over the Vredefort Mountain Land prior to updoming. Metamorphosed portion dotted.

Figure 17 is an ideal representation of the state of affairs prior to updoming, and shows the load lying horizontally and made up of the various formations in the relative thicknesses given in sub-section 1 above. A B represents the base of the Witwatersrand System. Load-metamorphism [1]) will extend upwards from A B through some unknown distance to the level C D, which, on the experience of field-evidence, is placed so as to embrace the Basal Amygdaloid and the bulk of the Water Tower Slates. The result is a layer of altered rock resting on the granite.

Figure 18 is an ideal picture (in plan) of the result of updoming and subsequent extensive denudation. Thus arises a circular area of central granite surrounded by an aureole (coarsely stippled) of hornblende-granulite (Basal Amygdaloid) and ferruginous garnet-amphibole-hornfels (Water

1) It is immaterial for the purposes of this argument, which particular view is taken of the cause of this metamorphism, i. e. whether it is wholly pre-updoming in date, or associated with the latter.

Tower Slates) ; a discussion of the cause of these tectonics is reserved for Chapter VI. In this way the effect of the Regional Component is established.

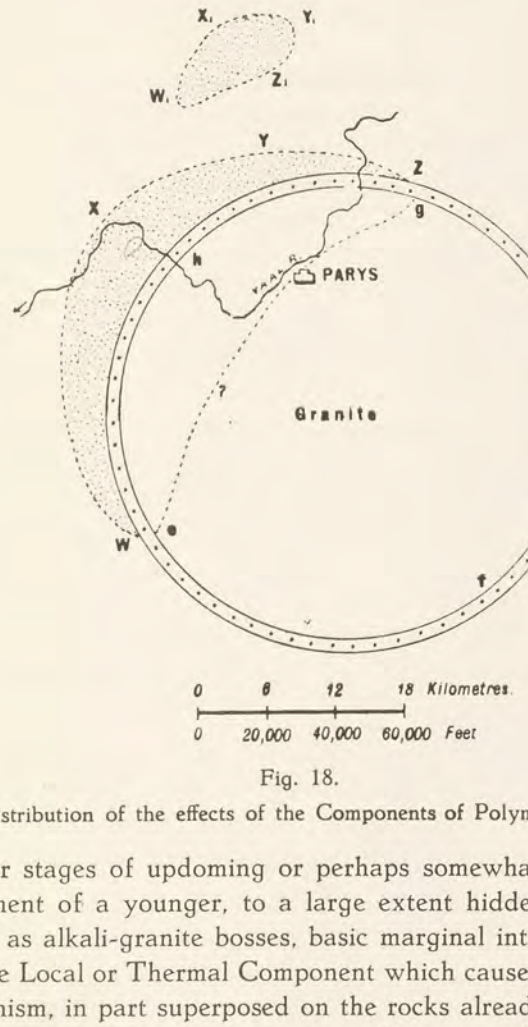

Fig. 18.

Ideal distribution of the effects of the Components of Polymetamorphism.

In the later stages of updoming or perhaps somewhat later still occurs the emplacement of a younger, to a large extent hidden, magma now in part exposed as alkali-granite bosses, basic marginal intrusions, etc. This body adds the Local or Thermal Component which causes the second phase of metamorphism, in part superposed on the rocks already subjected to the earlier or Regional Component, in part affecting rocks which had not previously suffered metamorphism.

The sphere of action due to the later Local Component (Thermal) alone, is indicated in figure 18 by the finely stippled areas wxyz (e.g. Koedoeslaagte, west-north-west of Parijs) and $w_1x_1y_1z_1$ (Rietfontein alkali-granite). The sector efg is the strip concerned only with the earlier Regional (Pressure) Component, (e.g. near Vredefort Road Station), while the strip ehg, which is common to both areas, represents the extent of superposed or polymetamorphism (from about Leeuwdoorns to Brakfontein).

In support of the above line of thought one may point to the fact that within the strip ghe the metamorphosed Water Tower Slates are often very coarse and extremely rich in garnet, while the hornblende-granulite of the Basal Amygdaloid is also distinctly coarser ; outside the same strip the corresponding rocks are less coarse or poorer in garnet, so that a kind of reinforcement of recrystallisation and a more vigorous growth of metamorphic minerals seems to be noticeable within the polymetamorphic zone ghe.

The region where the later or Local Component operated alone is clearly illustrated by the alteration of the dolomite round the alkali-granite boss on Rietfontein, some 20 km. north of Parijs. But it most likely covers the whole of the altered rocks of the Lower Witwatersrand System as far down as the Hospital Hill Quartzite. It may be suggested that the excessively coarse andalusite-cordierite-hornfels which is so striking round Baviaanskrans on Witbank may be due to a combination of two effects — close proximity (underground) of the Hidden Magma and local extension of the polymetamorphic strip, thus leading to a specially intense reinforcement.

The above views form the metamorphic picture of the Vredefort Mountain Land, as it is drawn by the writers after a long and detailed study of the evidence, and an intensive discussion of its theoretical aspects, with the due sense of the great difficulties of arriving at conclusions likely to command general assent.

The results may be summarized as follows:

1. The Vredefort Granite is not intrusive in the Witwatersrand System.

2. The alteration of this system is due to Polymetamorphism in two successive components, some parts of the metamorphic province having been subjected to one or other of these components, other parts to both (superposed metamorphism).

3. The earlier component is Regional, the essential agent being static pressure (with cooperation of heat).

4. Its effects are distributed concentrically so as to form a narrow ring of hornblende-granulite (Basal Amygdaloid), garnet-amphibole-hornfels (Water Tower Slates) etc. round the central granite.

5. Its cause is the load of superincumbent strata, perhaps in combination with orogenic forces during updoming of the granite.

6. The later component is Local, the esential agent being heat (with cooperation of pressure).

7. Its effects are distributed excentrically with reference to the granite circle and form an irregular area of cordierite-hornfels, andalusite-hornfels etc. up to 6.5 km.

wide, occupying the northern, north-western and western parts of the girdle of sediments.

8. *Its cause was the emplacement of a large younger intrusion,* to a great extent concealed, though exposed as three small bosses of alkali-granite, basic marginal intrusions in the granite, etc.

9. *Superposition of the Regional and Local Components* occurred along the segment stretching from about Leeuwdoorns on the west to somewhere near Brakfontein on the north. It tends to produce a reinforced metamorphism, indicated by coarser recrystallisation and increased size and abundance of some of the metamorphic minerals.

CHAPTER V.

The Tectonics of the Vredefort Mountain Land and Analogies with other Areas.

Though incidental reference has been made in previous pages to evidences of pressure, it is desirable, before discussing the geological history of the Mountain Land in which intense pressure plays such an important part, to present the principal traces which pressure has left in the structure and in the rocks.

A. The Tectonics of the Vredefort Mountain Land.

1. *Diastrophism prior to or contemporaneous with the intrusion of the Vredefort Granite.*

As stated in Chapter III, 2 we are of opinion that the schists on Blaauwboschpoort and other farms belong to the Swaziland System. They are older than the Vredefort Granite, which is proved by the fact that on Blaauwboschpoort and Witkopjes veins of pegmatite and aplite, which doubtless represent final products of activity of the magma which solidified as the Vredefort Granite, cut these schist-belts. The latter stand vertically or nearly so. Most probably they obtained their highly tilted position by orogenetic forces which took place prior to, or perhaps partly contemporaneous with, the period of original uptrusion of the magma of the Vredefort Granite.

This diastrophism probably belongs to the same period which embraced the tilting, folding and dynamic metamorphism of the sediments of the Swaziland System in other parts of the Transvaal. This first period of diastrophism in the Vredefort area far antedates that during which, after a long period of denudation, the Lower Witwatersrand System was laid down on the highly tilted strata of the Swaziland System and principally on the Vredefort Granite.

2. *Diastrophism connected with the updoming of the Vredefort area.*

In the doubtless very great lapse of time which stretches between the end of the deposition of the sediments of the Transvaal System and the beginning of the deposition of sediments belonging to the Karroo System a peculiar well localized and very powerful diastrophism took place in the Vredefort Mountain Land. Consequent on these crust-movements all round a common centre now occupied by the Vredefort Granite, all the sediments ranging from the base of the Witwatersrand System up to the top of the

Transvaal System were tilted and largely overtilted. In the centre of the disturbed area the Vredefort Granite was uptruded to a level, which, before it was lowered again by denudation, certainly must have been much higher than that occupied by the uppermost sediments of the Transvaal System. The result, as it can be seen now, is a boss of granite, the Vredefort granite-boss, encircled by a girdle of tilted and overtilted sediments. The total vertical displacement of the granite in the central portion of the Vredefort dome may be estimated to be more than 14000 m.

The granite was uptruded at the same time that the strata of the sediments were tilted and finally overtilted. What is the relation between these two phenomena? Has the granite played an active role in the process of updoming, or has it been moved upwards passively, following the uplift of the sedimentary roof?

Since the granite is clearly non-intrusive in the belt of sediments (see pp. 131—133) it is reasonable to surmise that is has played a passive role and has faithfully followed its sedimentary cover as the latter was arched up; evidently it was sufficiently plastic to follow the uptilting of the overlying strata in every detail. Yet the granite and the sediments did not respond in the same way to the updoming impulses. Consequently in some places, as e.g. on Zijferfontein and Tweefontein, the granite is faulted against (or perhaps thrusted over) the sediments, and at these places the lowermost portion is now hidden from view and the granite is brought in contact with shales which in their usual position overlie the Orange Grove Quartzites. In other places, e.g. on Witbank, Zijferfontein, and a portion of Rietpoort a narrow belt of sericitic schists is intercalated between the granite and the lowermost sediments, i.e. the Basal Amygdaloid, or in case the latter is wanting, the Orange Grove Quartzites; these schists are strongly sheared rocks and owe their origin most probably to differential movements between the granite-plug and the overlying sediments during the proces of updoming. In places these movements were concentrated in a somewhat higher horizon again indicated by the presence of sericitic schists. Thus, e.g. on a portion of Rietpoort a narrow belt of sericitic schists is in places intercalated between the Orange Grove Quartzites and the underlying Basal Amygdaloid.

The phenomenon of overtilting of such a huge block of sediments all round the central granite is one of the most remarkable features in the tectonics of this area and deserves closer attention.

The tilting and overtilting is not equally distributed all round the granite-boss, but both the intensity of the phenomenon and the horizon in which the maximum effect is obtained vary greatly. In a westerly direction from Vredefort via Leeuwdoorns to de Wet's drift the Lower Witwatersrand Beds dip about 70° towards the granite, as e.g. on Leeuwdoorns ; further away from the granite the overtilting increases and the strata of the upper portion of the Upper Witwatersrand Beds dip 58° towards the granite, as can be clearly seen in the beautiful section along the left bank of the Vaal

River, on the farm Elandslaagte [1]). Higher up in the belt of amygdaloidal diabase and porphyrites of the Ventersdorp System the overtilting is already much less, and the upper portion of this broad belt, as well as the poorly developed Black Reef Series and the Dolomite, at de Wet's Drift, stand vertical. The highest portion of the Dolomite Series as well as the lowest Gatsrand Beds, have not suffered any overtilting, but dip at a high and gradually decreasing angle away from the granite. Thus the zone of maximum overtilting in this direction is situated in the Upper Witwatersrand Beds. Due north of Parijs on the eastern portion of Rietpoort and on Brakfontein, the lower strata of the Witwatersrand System stand vertical or dip at a high angle towards the granite, but in the upper portion of the Upper Witwatersrand Beds the overtilting increases in intensity so rapidly, that in the very uppermost section the strata near the surface dip about 15°—20° towards the granite, and this almost entirely reversed position continues right through the belt of amygdaloidal diabase and the Black Reef Series into the lower portion of the Dolomite Series. Proceeding further north on Rietfontein we see the dip rapidly increase until the strata of the upper dolomite dip 70°—80° towards the granite or are tilted exactly at a right angle. The same is the case with the red shales and quartzites of the lowermost Gatsrand Beds which latter there crop out in a range of wooded, small, but abrupt hills. Higher up in the Gatsrand Series the tilting rapidly diminishes until comparatively soon the normal position is attained and flat-topped hills of the Table Mountain type, often crowned by sheets of diabase, make their appearance in the landscape. Thus in this direction the zone of maximum overtilting is found to extend from the very uppermost beds of the Witwatersrand System, through the Ventersdorp System and the Black Reef Series, right into the lowest portion of the Dolomite Series.

In a north-easterly direction from Vredefort towards Lindeque's Drift the strata of the entire Witwatersrand System and the amygdaloidal diabase of the Ventersdorp System stand vertical, or nearly so. The Black Reef Series and the lower portion of the Dolomite Series are slightly overtilted, but serious overtilting only makes its appearance in the upper portion of the Dolomite Series and in the lowest Gatsrand Beds, which dip about 60° towards the south-south-west, i. e. towards the granite. In higher horizons the overtilting soon disappears, and still higher the strata flatten out rapidly. Thus in this direction the zone of maximum disturbance and overtilting is found in the middle portion of the Transvaal System, at a distance of not less than 14 km. from the edge of the Vredefort Granite.

One must expect, as is schematically indicated in section fig. 12 that at a certain depth the overtilted strata will curve round and resume a normal dip. If this is correct, we should find the dip of the overtilted strata increasing in the direction of the dip, and in fact, in one particular case this increase could be actually observed. This happened in one of the incline

1) G. A. F. Molengraaff, **58**, p. 252 and Pl. X. fig. 8.

shafts made for prospecting purposes in the Upper Witwatersrand Beds on the farm Wonderboom. In this shaft the dip of the strongly overtilted quartzites and conglomerates increases within a distance of 65 feet from the surface from about 14° tot 20° 1).

At first sight the low angle (50°) at which in places, e. g. on the western portion of Rietpoort and on Witbank, the lowermost strata (the Orange Grove Quarzites) of the Lower Witwatersrand System appear to dip away under the granite, makes it somewhat difficult to believe that the strata in reality are overtilted, but a study of the sequence of the formations soon negatives any other conclusion. Moreover, the ripple-marks fig. 19 which are found in abundance on the layers of quartzite, specially in the Hospital Hill and Government Reef Quartzites, allow one to discriminate between the original upper and lower layers; a study of these phenomena proves that the strata in reality are in an overtilted position.

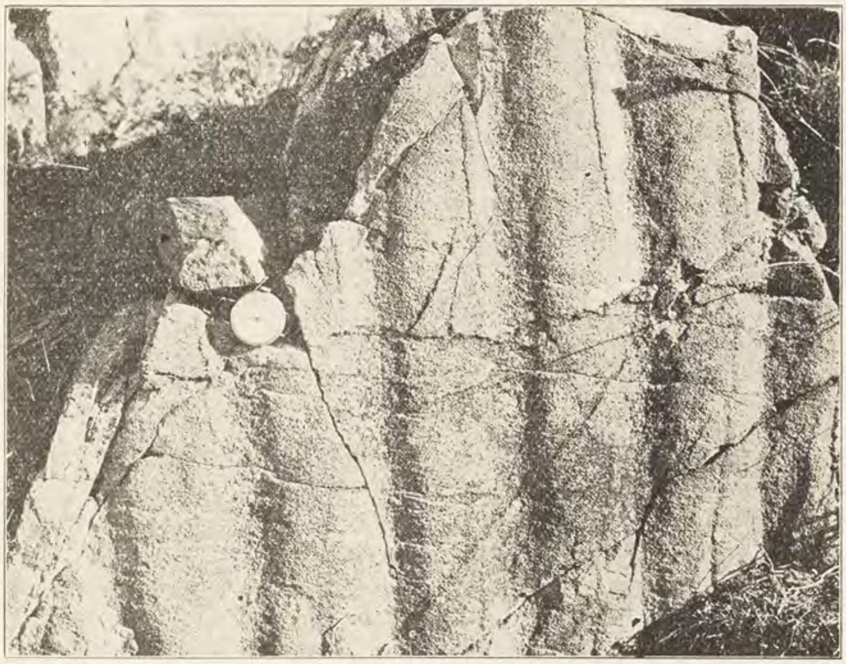

Fig. 19 *L. T. Nel phot.*

Inverted ripple-marks on Quartzite of the Government Reef Series on Waterpoortje 281.

The tilting and overtilting of a complex of about 13000 m. in thickness must have required almost incredible forces, and one of the marvellous features is that, taken as a whole, the strata now appear to be tilted and overtilted in such a regular fashion, and are comparatively little broken and disturbed. Gliding of the strata one over another has taken place, as could be expected, on an extensive scale, and has caused slicken-sides and polish

1) Surface-flattening, a kind of creep-phenomenon, appears to be excluded here.

on the planes of stratification, which phenomena can be well studied in the quartzite of the Hospital Hill Series in the Baviaansrand on Witbank and its continuation north of the Vaal River on Koedoeslaagte and Kopjeskraal.

Pure transverse and more or less oblique faults are fairly numerous, which proves, as could be expected, that the resistance to the disturbances was not quite equal in all directions. The transverse faults often cut through a considerable portion of the complex of tilted strata, as e.g. the big fault on Buffelshoek, but sometimes they only affect minor portions. The disturbances on Witbank are of peculiar interest, where the strata below the Hospital Hill Series are displaced by a system of more or less parallel transverse faults (Pl. XI fig. 1 and Pl. XXXVII), by which the big body of quartzite of the Hospital Hill Series in the Baviaansrand is not affected at all. Probably this particular system of faults is connected with the body of alkali-granite on Witbank and Koedoeslaagte, the intrusion of which has greatly disturbed the beds of the adjoining sediments.

The diastrophism in the Vredefort Mountain Land has been accompanied by considerable stress and pressure, causing all the rocks in that area to show more or less a cataclastic structure and to be cracked and crushed in many places. The effects of pressure are as a rule concentrated along crush-zones in which they may get so strong that the rocks are mylonised or triturated.

The rocks then are not rarely converted into rock-dust or ultra-mylonite in which the individual minerals even under the microscope are no longer recognisable. Finally, where the heat generated by this mechanical work is sufficient, the ultra-triturated material may be partly or wholly fused and then later solidify as flinty crush-rocks. Such flinty crush-rocks are found widespread in numerous localities as veins in all the rocks ranging from the Basement Granite well up into the Ventersdorp System. Microscopical examination proves that the crushing and grinding of the rocks was accompanied by comparatively little movement, and although the rocks affected are very rich in cracks and micro-faults, schistose structures are rarely formed. (See Chapter III, 8).

B. Geological Structures comparable to that of the Vredefort Area.

As far as the authors know, there are few structures which show a more or less close analogy to that of the Vredefort area.

The closest resemblance appears to be found in the Black Hills dome in South Dakota and Wyoming [1], and a certain similarity in structure is afforded by the Riës Kessel near Nördlingen [2].

1) Th. A. Jaggar, **40**. N. H. Darton, **17** and **18**. The beautiful almost circular dome of the Little Rocky Mountains standing isolated in the plains of Central Montana, though much smaller (about 11 km. in diameter) equally affords some interesting analogies to the structure of the Vredefort dome. Compare its description by L. H. Weed and L. V. Pirsson. **90***.

2) W. Branca and F. Fraas, **8**.

The three sections in fig. 20 are intended to supply a convenient comparison between those three structures, the peculiarities of each being given in the table printed below. (See Table pp. 152—153).

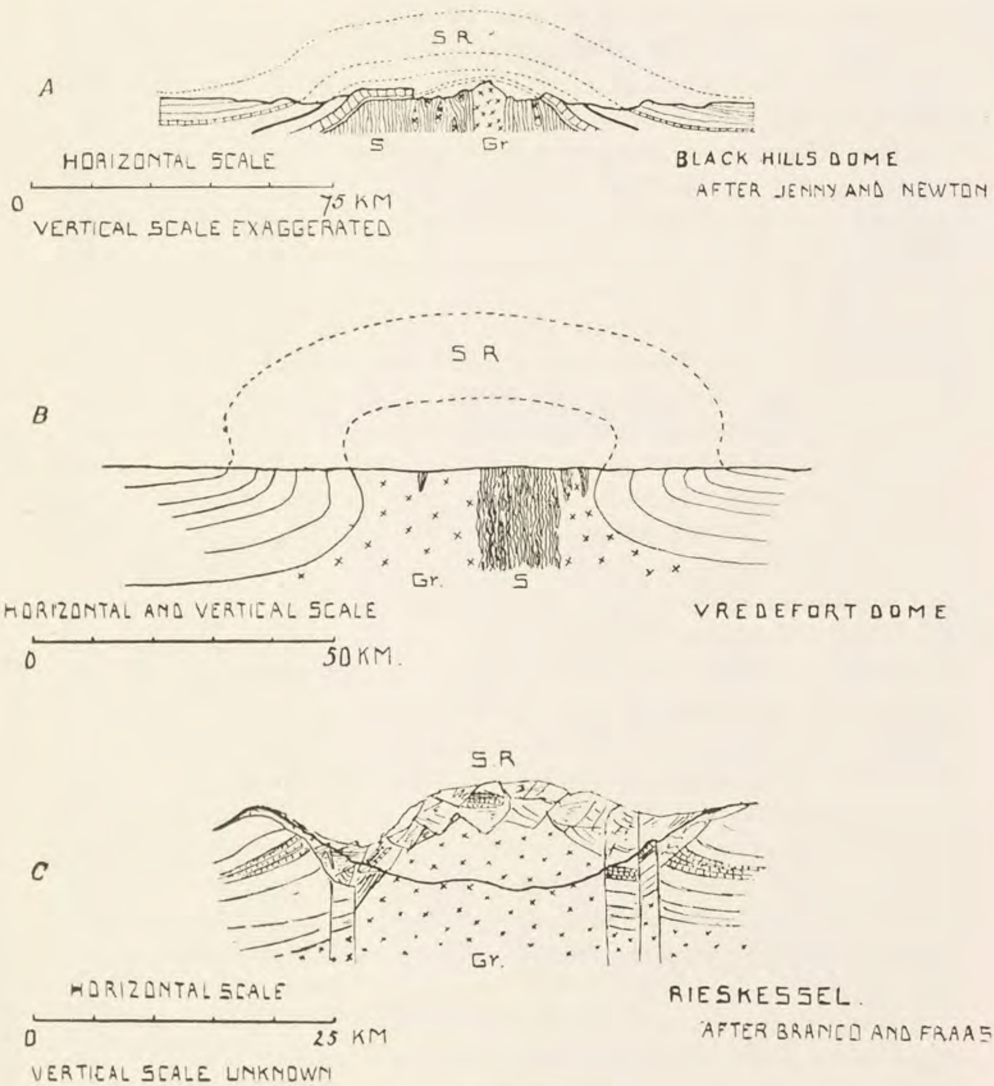

Fig. 20

Schematical sections of the Black Hills Dome, the Vredefort Dome and the Ries Kessel. S. Schists, Gr. Granite, S. R. Sedimentary Roof.

In shape Vredefort and Ries are strictly comparable, both being circular; the Black Hills dome with its oval shape standing apart. In size all three are sufficiently comparable.

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1) TH. A. JAGGAR, **40.**

2) W. BRANCA and F. FRAAS, **8.**

In the three structures the central core or plug (RUSSELL) is older, in all cases probably much older than the updomed sedimentary roof. The thickness of the updomed roof in the Vredefort dome far surpasses that in the other domes, and the same holds good for the probable vertical displacement in the central portion of the structure. The Vredefort dome is far the oldest of the three. There are great differences in the amount and the character of the tilting of the sediments as shown in the table, strong overtilting being characteristic for the Vredefort dome only.

In the Vredefort area the entire updoming movement originated at a much greater depth than in the Black Hills dome and this explains why phenomena of regional metamorphism and contact-metamorphism are so much more in evidence in the Vredefort area, where moreover the rocks cooled at a great depth and at a very slow rate.

In the Black Hills dome the roof over the central core is partly preserved, but at Vredefort and Ries it is destroyed, in the case of the Vredefort dome by erosion, in that of the Ries dome by volcanic eruptions and by erosion.

Igneous intrusions are found in the central granite-core in all three occurrences; in the sediments they are observed at the Black Hills and at Vredefort, but at the Ries, where they may have occurred, no trace of them is left.

In all three cases the observed facts lead to the surmise that a hidden igneous mass of magma must be present below the central core of granite and schists, the manifestations of which are excentric in the cases of the Black Hill and Vredefort. The Vredefort structure being much older than the others, the intrusions of material from the hidden magma there far antidates the igneous phenomena in the other structures.

Shattering and assimilation of the sediments invaded by the magma from the hidden mass are insignificant in the Black Hills, but strongly marked in the two remaining cases; hybrid rocks occur in the Vredefort area, and in the Ries Kessel they are developed on a very large scale. Magma from the hidden reservoir reached the surface causing volcanic eruptions in the case of the Ries Kessel only, which is easily explained by the superficial position of the Ries magma as compared with the position of the magma in the other structures.

Stress-phenomena are much in evidence both in the Vredefort and in the Ries domes, and attain a marvellous development in the Vredefort area, where they culminate in the genesis of flinty crush-rocks on a gigantic scale.

The most important point in the *explanation of the genesis of these structures* is doubtless the question of the primary cause of the updoming.

Two explanations deserve consideration:

1. The updoming is caused by a force acting from below upwards in the updomed area. The injection and ascent of a deep-seated igneous magma is the cause of the updoming.
2. The updoming is caused by forces acting in the earth's crust more

or less horizontally from all directions towards the centre of the uplifted area. Tangential stress in the earth's crust is the cause of the updoming.

Since it is admitted in the three localities mentioned above that the granite of the central core is of much older age than the phenomenon of updoming, and has played mainly or entirely a passive role during the process of updoming, the primary source of activity cannot be sought in the granite now exposed in the central portions of the three areas. Since, however, it is also admitted in all three cases that a magma of considerable bulk must have extended below the old granite either in a central or in an excentric position, it is reasonable to surmise the possibility that the activity and upward movement of this hidden magma itself was the primary cause, both of the uptrusion of the possibly semiplastic central granite and of the updoming of the sedimentary roof over this granite. This surmise would open the way to explain the majority of the observed facts. It is unreservedly accepted by BRANCA and FRAAS in the case of the Ries near Nördlingen. They believe that below or within the Ries Granite a laccolith of basaltic (gabbroid) composition became injected, which by its growth and its inherent force of uptrusion bulged up its cover composed of the central Ries Granite and with it also the roof of sediments at least 176 m. thick, resting on top of the granite. The profound alteration of the Ries Granite as well as the volcanic eruptions which accompanied the tectonic phenomena in their later stages are also due to the activity of the magma of this laccolith. It appears that all the observed phenomena, especially the circular shape of the huge „Kessel", the plug-like uptrusion of the granite and the formation of abundant hybrid rocks (suevites) are well explained by BRANCA and FRAAS, and notwithstanding many adverse criticisms the conclusion that the activity of a hidden magma in the shape of a laccolith below the Ries granite initially caused the peculiar structure of the Ries Kessel appears to be largely accepted now [1]).

Black Hills Dome. RUSSELL [2]) is of opinion that a deep-seated intrusion probably of highly viscous magma in or below the floor of metamorphic rocks and granite took place which raised the vast dome of sedimentary rocks and the floor on which they repose. The floor was pushed up like a plug. For such uplifts which owe their origin to the intrusion of a molten magma into the rock beneath them, RUSSELL proposes the term „subtuberant mountains" (**74**, p. 189).

JAGGAR combates RUSSELL's hypothesis (**40**, p. 287) and is of opinion that the uplift of the Black Hills dome was the result of orogenetic stress and deformation. Through such stress fractures were formed which released magma from the depths below (i. e. below the central core of schists and granite). Relative to the colossal orogenetic movements of uplift,

1) A. SAUER, **79**.
2) J. C. RUSSELL, **73** and **74**.

COMPARISON OF THE PRINCIPAL GEOLOGICAL FEATURES IN THE BLACK HILLS DOME

Geological features:	Black Hills Dome
Shape of dome	Oval
Diameter of total updomed area	70 × 128 km. approx.
Diameter of exposed central core	32 × 90 km.
Composition of central core	Algonkian schists with intrusive pre-Cambrian granite.
Thickness of updomed sedimentary roof	2000 m. approx.
Age of updomed sediments	Cambrian to Upper-Cretaceous.
Age of the updoming	Post-Laramie (Eocene)
Tilting of updomed strata	Strong to moderate and slight tilting.
Thermal Metamorphism	Not recorded.
Vertical displacement in central portion of dome	2750 m. (DARTON p. 549) approx.
Sedimentary roof over central core	Partly preserved.
Are intrusions of igneous rocks connected with the updoming?	Both in the central core and in the overlying sediments.
Are the igneous rocks restricted to a certain portion of the dome?	Their position is excentric and they are restricted to the northern portion of the dome exclusively.
Shape of the intrusions	Dykes in the old schists; sills and laccoliths in the covering sediments.
Composition of the igneous rocks.	Laccoliths, sills and dykes of grorudite, phonolite, tinguaite, rhyolite-porphyry, dacite, andesite-porphyry, diorite, diorite-porphyry and lamprophyre. (Irving).
Age of the intrusions	Eocene.
Shattering and assimilation of the invaded rocks; igneous breccias; hybrid rocks.	Invaded rocks are in places fractured and igneous breccias formed. (JAGGAR p. 188).
Volcanic phenomena	No evidence.
Stress-phenomena	Not much in evidence. Crush-breccias in limestone. Some faulting and fracturing of strata.
Flinty crush-rocks	Not recorded.
Pluglike vertical uptrusion of central granite core at a certain period of the updoming.	Not observed.

Vredefort Dome	Ries.
Circular.	Circular.
120 km. approx.	30 km. approx.
40 km.	25 km.
Granite intrusive in Archaean (?) schists.	Granite, probably of late-Carboniferous age.
12900 m. approx.	At least 176 m.
Lower Witwatersrand to Upper Transvaal System.	Keuper Series and Jura System.
Post-Pretorian and pre-Dwyka; older than late-Carboniferous.	Middle-Miocene.
Strong tilting to moderate and strong overtilting.	Very slight tilting.
Strong regional metamorphism in lower portion of sedimentary roof: strong contact-metamorphism caused by intrusion of igneous rocks.	Not recorded.
14000 m.?	340 m. approx.
Eroded away.	No more preserved.
Both in the central core and in the overlying sediments.	In the central core.
Their position is excentric and marginal to the granite core.	They are found all over the central granite-area.
Dykes, sills and bosses in the central granite; sills, dykes and stock-like laccoliths in the updomed sediments.	Dykes and necks.
Sills and dykes of gabbroid rocks; stock-like laccoliths of alkali-granites, dykes of nepheline-syenites.	Basaltic (gabbroid) rocks.
Post-Pretorian and Pre-Dwyka.	Middle-Miocene and later.
The invaded rocks are in places shattered and hybrid rocks and igneous breccias are formed.	Hybrid rocks (suevites) are formed in abundance.
No evidence.	In Upper Miocene time volcanic eruptions have occurred at many spots in the Rieskessel, especially along its margin.
Abundant and increasing in intensity towards centre of dome. Most in evidence at and near margin of central granite.	Crushing (Vergriesung) of central granite-plug (BRANCA p. 52) and of sediments in updomed roof.
Abundant, especially in, and marginal to, the central granite	Not recorded.
In some places indicated by marginal faults along the central granite.	Accepted for the Ries Granite by BRANCA and FRAAS.

folding and faulting, the igneous action was usually but an incident (**40**, p. 287). Intrusion is not conceived by him to have been in any sense a cause of the greater uplift, but an effect (**74**, p. 282).

JAGGAR (**40**, p. 187) says: „It seems reasonable to suppose, then, that the first release of igneous matter among the Paleozoic sediments of the Black Hills took place by permission rather than by aggression. After entering the sediments doubtless the magmas under pressure acted locally as violent deforming agents. The schists, filled with dykes, were forced apart laterally, the Cambrian charged with sheets and laccoliths was greatly expanded in thickness and deformed horizontally, and the great limestone was domed up over the Terry Peak district as a whole and was locally pimpled and punctured by the small outlying masses. Thus intrusive action in the scheme of geologic deforming forces is both effect and cause; irruption is an effect of orogenic fracturing, a cause of localized doming and faulting."

On page 280 JAGGAR concludes: „In the preceding pages it has been shown that igneous intrusions accompanied or immediately followed a great movement or uplift in the area now occupied by the Black Hills. This uplift arched the horizontal strata of the plains into an elongate dome; schists beneath, with nearly vertical bedding and lamination, moved up by faulting and slipping, frequently on planes of schistosity...... The igneous matter rose through the steeply inclined schist laminae and spread out among the sediments which lay across them unconformably. Erosion leveling has exposed dykes in the schists and flat masses (laccoliths) in the later strata."

DARTON (**18**, p. 62) points out that the Black Hills rise at the north end of an anticlinal axis extending northward from the Laramie or Front Range of the Rocky Mountains.

The Black Hill dome with its oval shape is genetically strictly comparable to the neighbouring hills of this Front Range which are, however, more elongated and consist of huge anticlines and are the result of strong orogenetic deformations. MELLARD READE [1]) referring to the Black Hills of Dakota says: „It is a great and striking instance of elevation by centripetal compression and vertical uplift."

In the case of the Vredefort Dome the surmise that a deep-seated intrusion in the central core of granite and schists underneath the now visible surface has taken place and has by its own inherent force raised the huge dome of sedimentary rocks as well as the floor of old granite and schists on which they repose would go far to explain the observed facts. It would fairly well explain the circular shape of the dome, although it remains unexplained and difficult to understand why the centre of the hidden intrusive mass does not coincide with the centre of the dome. It would well

1) T. MELLARD READE **75**, p. 231.

explain the fact, that the intruded magma stood under pressure and locally had a strong deforming influence on the invaded sedimentary strata.

It is, however, not easy to conceive how the intrusion of this deep-seated mass, the visible offshoots and injections of which have but moderate dimensions, could accomplish such stupendous work as to lift the weight of a complex of sedimentary rocks about 13000 m. thick, as well as an underlying thick floor of granite and schists, and to bulge up this entire mass giving it the shape of a huge dome, which in its centre must have moved upwards at all events more than 14000 m.; at least if we imagine that all this work was done by the ascending force of the magma alone without the aid of orogenetic movements in the earth's crust. Further it is difficult to imagine why the strata of the sedimentary roof of the dome were not only tilted at a high angle, but were largely overtilted at many places and over great thicknesses. Finally, it is not quite evident, why in the Vredefort dome, if it were pushed up by igneous forces from below, phenomena of intense stress and pressure are so prevalent and developed on such an enormous scale. One would rather expect, on this assumption, conditions of tension during the updoming to be developed in the roof, and consequently to find the roof now to be intersected by dykes of the uptruded magma; in reality sills are plentiful in what is left of the roof now, but dykes very scarce.

Some of these difficulties appear to be removed if one accepts that the primary cause of the updoming is an orogenetic one and that centripetal stresses in the earth's crust caused the horizontal strata and with them the underlying floor of granite and schists to be elevated and arched up into a huge circular dome. If one admits the plane of application of the centripetal forces to have been lower than the present visible surface of the granite, an overtilted position of the strata in the lowermost portion of the slope of the dome could be expected. Further, the intense stress, the effects of which are visible in all the rocks throughout the Vredefort area is, on this assumption, of necessity the result of the powerful pressure which resulted in the updoming of a huge block of the earth's crust.

The magma in the depth below the central granite was released by the local relief of pressure due to the updoming, and got the opportunity to invade with force the much heated and probably semiplastic granitic floor as well as the roof of the dome. Differences in the capacity to which the various roof strata were able to resist pressure would give the ascending magma during the updoming an opportunity to be injected as sills. The intrusion of the magma from beneath thus is considered not to be the cause or at least not the only cause of the uplift of the dome, but an effect. This explanation is similar to that given by JAGGAR in the case of the Black Hills dome.

Accepting this explanation, a serious difficulty, however, arises from the perfectly circular shape of the affected area. There is no main axis of dislocation perpendicular to which the lateral pressure was exerted, as occurs in mountain-chains; on the contrary we find a huge and almost perfectly circular and symmetrical structure, the trend of the tilting and overtilting gradually changing in direction all round the granite-boss. Even the Black Hills dome which has a great general analogy with the Vredefort dome is not circular, but oval, and its structure is closely allied to that of neighbouring mountain-groups in the Front Range of the Rocky Mountains which are much more elongated and show an anticlinal build.

The Vredefort dome apparently stands quite alone and there are no comparable structures found in its neighbourhood 1) which might assist in solving the problem of its origin. Thus, if admitting the Vredefort dome to be exclusively or mainly the result of centripetal compression in the earth's crust, one is compelled to regard this structure as a unique one, the exact analogy of which has not yet been observed elsewhere 2).

Whichever of the two suggested explanations one might accept, the reason why the updoming in both cases happened to take place where we see it now and not somewhere else, and therefore its initial cause, remains unexplained. A certain indication may be found in the fact that at the end of the period of deposition of the Transvaal System the Vredefort area formed the deepest point, or at all events formed part of the deepest portion of a geosynclinal area, in which an uncommonly thick prism of sediments has accumulated (fig. 16).

MELLARD READE 3) and later BOWIE 4) and SANDBERG 5) have elucidated, how the rise in temperature of thick prisms of sediments which by their accumulation and consequent sinking in geosynclinal areas are brought within the domains of high temperature (in the Vredefort area probably about 400°) may lead to their upward movement, either by thermal expansion (MELLARD READE) or by molecular processes increasing their volume combined with some thermal expansion (BOWIE) or by the expanding force of their connate water (SANDBERG).

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1) It must be admitted that after the close of the era of deposition of the Transvaal System, and in the same period of time in which the Vredefort dome came into existence, in the Witwatersrand area also some updoming took place, albeit on a much smaller scale than in the Vredefort area. This is proved by the fact that the strata of the Black Reef Series and the overlying Dolomite gently dip away in all directions from the area now occupied by the Witwatersrand and the granite-boss north of it. This uplift in the Witwatersrand area is very feeble and it is doubtful whether it is a feature, genetically at all comparable to the intense updoming in the Vredefort area.

2) As to its shape the dome of the Little Rocky Mountains which is nearly circular (only slightly oval) most of all comparable structures resembles the Vredefort dome.

3) T. MELLARD READE, **75**, pp. 8—11 and 92—95.

4) W. BOWIE, **7**, p. 191.

5) C. G. S. SANDBERG, **78**, p. 46.

CHAPTER VI.

The Geological History of the Vredefort Mountain Land.

In trying to trace the geological history of the Vredefort Mountain Land, the authors reach the most difficult and controversial part of their subject; it would be disappointing, however, to leave the complex descriptive detail presented in the preceding pages without some attempt to unravel the major magmatic and tectonic events, arrange their sequence and suggest their causes. It is hardly necessary to point out that into such an effort some amount of speculation must enter, neither is it possible to avoid making some postulate.

A. The Fundamentals of the Problem.

The reader will have gathered that the geological history must be so written as to satisfy the following outstanding conditions clearly established in the geology of the district :

1. An almost truly circular area of relatively passive non-intrusive Vredefort Granite, surrounded by
2. A girdle of highly inclined and often overtilted younger sediments extending from the base of the Witwatersrand System upwards through not less than 10.000 m. of thickness, and frequently seen dipping into the central granite.
3. Within this girdle a strongly marked polymetamorphism, of which one phase carries its effects concentrically all round the granite, while the other distributes its results excentrically to that formation.

The above are the most striking and the most puzzling features; any explanation must conform to them. If it can be so formulated as to lead inevitably to the above three fundamental factors, the remaining features, e.g. the form and distribution of the interior basic marginal intrusions, or the extraordinary abundance of flinty crush-rocks etc. are less difficult to assign their proper places in the sequence of events, and to recognise as resultants from particular causes.

B. The Pre-Updoming Period.

In previous pages the writers have repeatedly made use of the term "up-doming", and it is desirable to explain its significance. It is clear that the appearance of the Vredefort Granite at the surface to-day is due to the removal by denudation of the overlying capping of Karroo (and perhaps other younger) formations. This result depends, however, on the antecedent condition that the central granite was raised from below its great covering consisting of the Witwatersrand, Ventersdorp and Transvaal Systems ; there is no reasonable doubt that these formations occupied at one time an areal distribution and continuity far in excess of that seen to-day. It is this raising of the granitic floor carrying the formations referred to, that is understood by the expression of "up-doming", and this diastrophism must have been completed prior (at least) to the deposition of the basal portion of the Karroo System, since the latter was most certainly never affected by any incident in the magmatic or tectonic changes now traceable in the Vredefort Mountain Land.

The oldest geological event in the Vredefort area, of which any record is left in the existing rocks, is the deposition of a system of strata accepted to represent the Swaziland System. The age of this system is unknown and it comprises different ancient formations which probably all are older than the Witwatersrand Beds [1]). The strata of this system were metamorphosed into schists and intensely folded with a prevailing East-West strike.

A granite-mass now known as the Vredefort Granite was intruded in this system, the intrusion being accompanied by injections of pegmatite and aplite which now form numerous veins both in the granite and in the schists. It is believed that this granite is equivalent to and of the same age as the Old or Grey Granite and gneisses which cover very large areas in the north of the Cape Province and in the Transvaal. It is unknown whether the intrusion of this granite took place contemporaneous with the folding of the strata of the Swaziland System or later.

After a long period of denudation and planation of the country built up by the just-mentioned formations, the strata of the Witwatersrand System were deposited unconformably on the highly tilted Swaziland schists and the Vredefort Granite. Later the strata of the Ventersdorp System and the Transvaal System were laid down successively in apparent conformity on those of the Witwatersrand System. The unconformabilities which are in evidence in many localities in the Transvaal between the Witwatersrand System and the Ventersdorp System, and again between the Ventersdorp System and the Transvaal System are not observed in the Vredefort area, but make it necessary to accept the existence of time-intervals between the periods of deposition of these Systems.

The cycle of sedimentation is completed with the deposition of the Pretoria Series [2]), when a succession not less than some 13000 m. in thickness rests on a granitic floor. This granite is destined to become

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1) A. W. ROGERS, 72.

2) In the Vredefort Mountain Land the Pretoria Series is represented by the Gatsrand Beds.

ultimately the Vredefort Granite, which may, however, have developed some modifications as the result of the updoming and its accompanying tectonics.

The base of the succession is a region under a superincumbent load due to a succession having the thickness referred to above, where the temperature and pressure would be in the neighbourhood of 400° C and 3500 atmospheres (see Chapter IV, C). The conditions just specified tend to call into play the changes previously discussed as the Regional Element of Polymetamorphism, in which metamorphism due to pressure consequent upon load is the dominant agent ; heat, however, is by no means excluded. Whether or not the geological conditions, as they may be visualised at the close of the cycle of deposition, are sufficient to fully establish the results of Regional Metamorphism will depend upon the view that may be taken of the efficiency of load, i.e. the combination of high pressure with fairly high temperature. If the reader is satisfied that the first suggestion, made in Section C of Chapter IV for the causes of the Regional Element of polymetamorphism, is adequate, then already during the pre-Updoming Period an earlier group of recrystallised metamorphic rocks resting upon the granite will gradually have become established. If, on the other hand, the intensity of load-pressure alone (even with fairly high temperature) is regarded as inadequate, and is held to require reinforcement through additional pressure arising from up-doming and orogenic movement, then, according to the second suggestion, that group will not have become fully established until updoming has begun. It is probable, however, that the view one takes on this point would not essentially affect one's choice of the principles determining the remaining stages in the geological history.

C. The Updoming Period.

The term „Updoming Period" is used to denote that stage in the geological history which begins with the raising of the granite floor, embraces all the orogenic and magmatic phenomena, e.g. bending up and overtilting of the strata, intrusion of younger alkali-granite, etc., and ending through the relief of intensified pressure with the establishment of many faults, and of countless flinty crush-rocks as the concluding episode.

It is not known what interval elapsed between the close of the cycle of deposition and the commencement of up-doming, but the maximum of such interval must clearly correspond to the period which reaches from the top of the Transvaal to the beginning of the Karroo System. It is probable, however, that the updoming, with its attendant or subsequent tectonic and magmatic activities, was at any rate to a large extent, if not wholly, completed, before the Waterberg System began to be laid down, since it is now known [1]) that the emplacement of the Busveld Igneous Complex is of pre-

1) R. A. Daly and G. A. F. Molengraaff, **16**.

Waterberg age, and certain aspects in the geology of the Vredefort Mountain Land (referred to below) render the view admissible that the tectonics and igneous events in the area belong to and are somehow genetically connected, though not necessarily altogether contemporaneous, with the period of igneous activity embraced by the Bushveld Complex episode. On this view the Updoming period falls within the interval stretching from the top of the Pretoria Series to the base of the true Waterberg (formerly so-called Upper Waterberg) System.

On the other hand, it is not excluded that the igneous activity — though a phase of a major epoch covering both areas — began and ended somewhat later over the Vredefort Mountain Land than it did over the Bushveld, and may possibly even overlap into the early (true) Waterberg period.

1. *Causes of the Updoming.*

Anyone occupying a suitable point within the central granite — e.g. the high ground of the Parijs Commonage — and studying the regular amphitheatre determining his horizon cannot fail to realise the striking aspects of the first two fundamentals of the problem stated above. The grand simplicity of the design at once suggests a corresponding broad simplicity in the major cause; almost inevitably one is reminded of the ring-like features displayed by the craters of the moon, or of the physiography accompanying a gigantic caldera, of the „Maare" of the Laacher See in the volcanic region of the Eifel, or even of the geological history of the Rieskessel in Bavaria. The authors do not wish to suggest, however, that such analogies necessarily possess genetic significance in the case of the Vredefort Mountain Land.

The types of diastrophism which could inevitably lead to the broad symmetry so strikingly displayed in the distribution of the Mountain Land and at the same time establish a system of dips radially directed towards a central area are very few. Two sets of activities suggest themselves as possibly adequate; the one is based on vertical movement and the other on centripetal pressure.

Regarding the first conception of vertical movement, this may have been downwards or upwards. Now it is fairly clear that subsidence could not have led to an overturning and consequent inversion of the succession, such as is established beyond doubt. Although there are several features, such as the flinty crush-rocks, fault-intrusions etc. within our area which recall the remarkable cauldron-subsidence of Glen Coe [1]), the peculiar history of the latter region is not directly applicable to the Vredefort Mountain Land; still there are close points of contact in some of the pressure-effects. To bring about the overtilting of

1) E. B. Bailey and H. B. Maufe, 3.

the sediments resting on the central granite, vertical movement downwards is therefore inadequate.

It is impossible to resist the conclusion that vertical movement could have been concerned in the tectonic history of the Vredefort Mountain Land only as upward movement, in the nature of an uplift. Such diastrophism could be brought about by the gradual rising up of a younger magma; while there is direct evidence for the existence of such an intrusive, and to a large extent hidden, reservoir (e.g. alkali-granite-bosses), the question arises, is this younger magma adequate to produce the observed tectonic phenomena if regarded as their sole cause?

The severe limitations imposed on the nature and *modus operandi* of the updoming caused by the striking symmetry of the result, presupposed a centrically situated uprising magma, yet the position of its visible portions and in particular the distribution of its metamorphic effects, as explained in Chapter IV, indicate that this magma is distinctly excentric towards the Vredefort Granite. Given the requisite energy, it is not difficult to see that an upward pressing magma using a relatively passive roof of Vredefort Granite as a kind of buffer, could raise, bend up, and finally tilt a considerable thickness of overlying sediments, but it is very difficult to realise how actual overtilting could be thus brought about on the observed scale.

For these reasons the authors are of opinion that a vertical uplift based on a rising younger magma is inadequate, if regarded as the sole cause of updoming.

Bearing in mind, however, that the emplacement of the visible offshoot of the younger magma was concluded before the final establishment of all the results of updoming (as shown by the distribution of the flinty crush-rocks) and recalling the intimate and frequent association between crustal deformation and magmatic activity, they are not prepared to deny the vertical uplift based on such a magma a share in the mechanism of updoming, but are inclined to regard it as an important contributory agent in this diastrophism.

Regarding the second conception of centripetal pressure, one may conceive this to have been effected through a system of radially directed tangential pressures converging on the area now covered by the Vredefort Granite. Such a system of forces would tend to arch up this area and — if symmetrical in distribution and intensity — eventually to produce an equally symmetrical overtilting and underthrusting. It would, however, be too much to expect such a high degree of symmetry, and the unequal degree of overtilting, described in Chapter V appears to indicate that the postulated centripetal pressure was not equally intense all round. Underthrusting would be almost inevitable, and a strong indication of its actual occurrence is provided by the enstatite-granophyre dykes. These sometimes run inside the central granite at a considerable distance from its periphery, and their countless xenoliths of quartzite — obviously not derived from the granite must clearly be traced to masses of quartzite now underlying the granite. In other words, the quartzite-beds were thrust under the granite. Locally, no doubt, a system of sub-parallel thrust-planes might easily be developed, slicing up the lowest portions of the Lower Witwatersrand System into a series of ,,thrust sheets". Displacements of the latter could become so adjusted, that here and there portions of the succession were "thrust out", bringing a higher horizon to lie against the granite. Such a result appears to be exemplified on Zijferfontein east of Parijs, where the ferruginous Water Tower Slates are in direct contact with the granite — without any intervening Orange Grove Quartzite. Some degree of folding would also be almost inevitable, yet actual folds were not observed round the central granite, though there is abundant evidence of folding over wide areas immediately beyond the Vredefort Mountain Land (e.g. Potchefstroom syncline).

The authors regard centripetal pressure as the major cause of Updoming and, on the basis of the preceding discussions, formulate the genetic postulate as follows :

Postulate : The present structure of the Vredefort Mountain Land is based on centripetal pressure as the major cause, associated with a "point" uplift as a minor cause and dependent upon the emplacement of a younger magma. The combined result is the Updoming of the central granite as a more or less passive body[1]).

Before considering the results of applying the above twofold postulate, it must be pointed out that its minor phase is not in a literal sense, a "point" uplift. This term is used to emphasize the idea that the upward movement had radial and not axial symmetry.

It is not excluded that in so far as the upward movement depended upon magmatic adjustments, these were such as might have resulted, under different circumstances, in one or other of those essentially volcanic analogies, already referred to. The authors realise that it would be highly speculative to make any definite suggestions as to whether or not the upward movement was sufficiently intense and prolonged to result in volcanic activity, in terms of which the central granite might be looked upon as marking the site of an ancient volcano ; one obvious difficulty — the complete absence of volcanic rocks — would, however, not be insuperable, since they might have been entirely removed by denudation — a result also suggested for other regions[2]). In the arching up of the sediments, the roof of the upward pressed granite would be subjected to very great tension;

1) JORISSEN, in 1906, and SANDBERG, in 1907, assumed centripetal pressure in the earth's crust to be the cause of the updoming of the Vredefort area (compare p. 7).

2) A. HARKER, **32**, suggests that the absence of volcanic rocks in the Lewisian System of North-West Scotland is due to their removal by Pre-Torridonian erosion.

if the superincumbent load was inadequate, the roof must have shattered, thus providing an outlet for effusive rocks. This line of thought leads to the very great difficulty of realising how the core or the root of the activity would have become occupied by a plug of granite. The more reasonable and less hazardous suggestion is to assume that the roof, though no doubt under a great tension, was yet strong enough to prevent magmatic material bursting through to the surface ; on this suggestion the passive granite was used as a kind of punch or buffer and was consequently subjected to very great stress.

In so far, therefore, as the idea of some form of volcanic activity may appear to be implied by the minor phase of the postulate, no such activity is contemplated beyond an uplift of a *potentially* — not actually — volcanic nature.

The twofold character of the postulate raises the question of the relationship between its major and minor phases. As regards the time order, the authors consider that the centripetal pressure came into force first, to be followed later on by movements of magma. As regards genetic relationships they believe that as a result of centripetal pressure there was a local relief of load which allowed an upward movement of molten magma, so that the minor phase of uplift has the major phase of centripetal pressure for its cause [1]). It is by no means impossible that this ascent of magma may have enabled the results of centripetal pressure to impress themselves with a degree of symmetry higher than that which would have resulted from the operation of the major phase alone ; this conclusion does not require a centrically disposed underground reservoir, but only one that lay near enough to the focus of convergent pressures to respond to the relief of superincumbent weight provided by the system of centripetal forces.

2. *The Results of Updoming.*

It has been pointed out that the uplift is associated with the emplacement of a younger magma, and that the writers lean to the view that the uplift preceded the emplacement, which was aided by relief of pressure consequent upon updoming.

Accepting, therefore, a wider interpretation of the causes of Updoming, so as to include an uplift as well as a phase of major intrusions, the results of updoming are concerned with the following three sets of phenomena : — Tectonic, Magmatic, and Metamorphic. This enumeration probably also indicates the time order of the principal events, with a limitation with respect to the tectonic set, as explained below.

a. *Tectonic Results.* These are the first to become established, but the great variety of formations affected by faults or having veins of flinty

1) The initial cause of the centripetal pressure in the earth's crust remains unexplained (compare p. 156).

crush-rocks, clearly indicates that pressure-influences operated for a very long period and overlapped the magmatic and metamorphic phenomena in time. This experience agrees with the almost inevitable *a priori* conclusion that the arching up and overtilting of a great succession of sediments must have required a long period of time. Pressure is clearly the dominant factor moulding the tectonic results.

The initial effect of centripetal pressure will be comparable to a gathering up of the highest beds of the sedimentary covering, accompanied almost certainly by much puckering, folding and other tectonic changes. As this pressure continues, a gradually increasing thickness of sediments will be so effected, and when there has resulted sufficient relief of load, the minor phase of vertical uplift will gather strengh and assist the tilting and overtilting; in this way the passive granite is at last itself affected and eventually updomed. During these changes the sediments were not only arched up, but must have been stretched and disrupted ; yet in the lower levels of the sedimentary covering, folds would be less readily formed owing to the increasing superincumbent weight. The initial tectonic results are not now in evidence, owing to denudation — the sedimentary roof of the updomed area being completely denuded away — but what one actually sees is only the more uniform tilting and overtilting, as is was developed in the lower portions of the slope of the dome. This is probably why no folding is preserved in the Mountain Land nearest the central granite.

During this slow diastrophism the pressure is probably intensified progressively until a point is reached where the sediments nearest to the granitic plug can no longer resist the stress but yield here and there along faults or other planes of dislocation. Hence arises the great system of dip and oblique faults seen at many points in the Lower Witwatersrand System. At the same time the periphery of the central granite along its contact with the basal portion of the girdle of sediments is a plane of weakness, because here two groups of rocks meet, one igneous (granite) and essentially uniform in strengh, the other built up of a series of stratified formations likely to offer a variable degree of resistance to mechanical deformation, and differing from the granite in the readiness with which they respond to stress. On such a line of reasoning, one would expect to find the maximum effect of faulting within the Lower Witwatersrand System at or near its peripheral granite-contact. This is exactly what one does find. Furthermore, some amount of differential movement seems inevitable along that contact and would lead to a local rolling out of any more resistant sediments. This anticipation is likewise realised — i.e. the sericite schists (sheared quartzites) at the base of the Orange Grove Quartzite group east of Parijs. It is quite possible that locally the granite itself may pass into such schists as a result of shearing.

So far we have considered only the tectonic effects of pressure on the girdle of sediments ; the granite itself, however, cannot and did not escape these influences. Quite apart from the postulate of the writers, there is abundant evidence that the granite also suffered deformation under more or less rigid conditions. This has been referred to in previous chapters, and is established beyond question, e.g. by the great abundance of flinty crush-rocks with their phenomena of trituration and mylonitisation, by crush-lines of quartz-mosaic etc. Quite another mechanical effect on the granite, however, must now be emphasized.

On the hypothesis that the central granite acted as a more or less rigid punch or buffer one is led to anticipate a tendency for a system of *potential* planes of discontinuity to become established, disposed concentrically with the upward arched surface of contact. One may perhaps refer to the analogy of a steel pestle, over the curved surface of which — after long use — one often observes a similar tendency for the material to peel off or exfoliate in thin leaves corresponding to planes of weakness running with the curved surface of impact. Now attention was called in chapter III, to the remarkable forms assumed by the basic interior marginal intrusions, which sometimes are more or less vertical bodies, but continue now and then as almost horizontal sheets into the granite — as if there were planes of weakness in the latter. This experience suggests something of the nature of a very crude tectonic exfoliation along potential planes of weakness induced in the granite by its having been subjected to intense pressure — like a form of excessively coarse "pseudo-gneissic" structure. In this way the postulate of the writers seems to entail tectonic consequences within the granite, that are borne out by the field relationships of the marginal basic intrusions also.

The latter themselves, whether one considers those falling within the granite (interior) or within the adjoining sediments (exterior), by their restriction to the proximity to the peripheral contact-zone and by their reduced display higher up in the sediments, tend to confirm the conclusion that this contact-zone represents a belt of structural weakness and thus predisposes a concentration of emplacements over such zone.

At the period of maximum pressure, i.e. after the thorough arching up of the strata, perhaps even after the commencement of the faulting stage, the pressure is so great that the essentially still rigid granitic ,,buffer" (as well as the girdle of sediments) begins to crack in many places. This result occurs locally, and though the cracks are not extensive, they are very numerous, and develop into crush-lines, along which a system of flinty crush-veins are formed. This is the pseudo-tachylyte chapter in the history, but it must have extended in time until after the magmatic and metamorphic phenomena were completed, for one finds such crush-veins in the alkali-granite, in the interior basic marginal intrusions, in the hornfels etc. Since "pseudo-tachylyte" is found in these marginal intrusions, the establishment of potential planes of weakness within granite — into which basic material could be intruded in sheet-form — must have preceded the development of at any rate some of the flinty crush-rocks.

Attention has been called in Chapter III Section 8 not only to the extraordinary abundance of flinty crush-rocks, but also to their remarkably wide distribution through the succession upwards; they are almost incredibly abundant in the central granite and in the Lower Witwatersrand System, but they have also been observed as high stratigraphically as the Ventersdorp System, yet their display undoubtedly dies off radially outwards from the granite. This tends to show that the tectonics affected an area well in excess of that covered by the central granite and its contiguous sedimentary girdle. This is, however, consistent with the postulated causes of the Updoming.

The phenomena of crush given in the earlier section (Chapter III, 8) dealing with the so-called pseudo-tachylyte leave no reasonable doubt, that there must have been an occasional local fusion of the material from which certain phases of flinty crush-rocks were derived. It is doubtless difficult to realise that pressure alone should produce actual fusion, but it should be remembered that besides the rise of temperature due to load, there is the contributing factor of heat generated by mechanical deformation. The latter is not generally held to have much weight, and rightly so, but in an area like the Vredefort Mountain Land with its abundant and striking evidence of terrific pressure, adequate to cause overtilting of sediments on probably an unprecedented scale, it may well have been the case that the additional heat-factor dependent upon intense stress was just sufficient to turn the scale in favour of a result which could not have eventuated otherwise. The reader is reminded of that unique rock described as enstatite-granophyre, which no one who has studied it in the field would hesitate to class as a dyke-intrusion resulting from igneous fusion. Yet this rock has an extraordinary number of strained and crushed xenoliths — not found in any other group of intrusions in this area; such xenoliths are intensely characteristic of almost all the flinty crush-rocks of the district. It is impossible to resist the conclusion that the enstatite-granophyre is a "glorified" form of pseudo-tachylyte and emplaced as molten material; from it as the most spectacular form there is every gradation down to minute stringers of pseudo-tachylyte without any change in essential petrographical features.

These are the principal tectonic phenomena that would appear to follow from the postulated causes of updoming, but in the case of the granite there is another effect to be considered in connection with the metamorphic results (See below under c).

b. Magmatic Results. According to the writers' views Updoming was associated with a major intrusion, or rather a group of such intrusions. The latter comprise an earlier basic and a slightly later acid group, though most probably the greater portion — specially of the acid phase — is still concealed.

The earlier type is thoroughly basic and comprises the marginal intrusions — both interior and exterior — described in Section 7 of Chapter III, where the striking petrographical or chemical similarities between those formed within the granite close to its periphery and those occurring in the Lower Witwatersrand System — specially abundant nearer its base — are discussed. They are regarded as earlier than the acid group on account of the field-relationships seen e.g. along the Witbank section, where the emplacement of the alkali-granite has resulted in a displacement of the Hospital Hill Quartzite and horizons stratigraphically below it — including some basic intrusions. The dislocations seen in this and adjoining regions clearly indicate that the basic group had reached its present position before the tectonic effects had become sufficiently intense to be relieved by faults ; this suggests the following order of events during the period of updoming : — First the creation of those potential planes of weakness in the central granite referred to in the previous section as a form of "tectonic exfoliation", then the emplacement of some of the basic interior mariginal intrusions along such planes and of others along the strata of the Lower Witwatersrand System, and lastly movement along faults as a result of increasing pressure. The great prevalence of this group at or close to the granite-periphery is most probably related to the tectonic aspects discussed above, and reference has already been made to the variable forms assumed by the interior marginal intrusions as a result of the intense stress to which the Vredefort Granite was subjected during its Updoming.

Since the faults in the girdle of sediments displace the marginal intrusions, the latter must have been already emplaced before the faults, as stated above, occurred. This result may be interpreted in two ways.

In the first place, it is possible that the emplacement of the basic intrusions, though anterior to the faulting stage, may yet belong to the Updoming Period and to fall within its initial stages, without being independent and long anterior to the whole of the updoming events. This is the view indicated above ; it is closely analogous to the relationship between the great diabase-sheets round Pretoria and the powerful faults displacing them — phenomena all genetically connected with the magmatic and tectonic events of the Bushveld Complex.

In the second place, one may interpret the faulting of the basic intrusions round Parijs as denoting a more or less substantial time-interval between the emplacement and the updoming, with its faulting, occurred. This view fails to explain the strictly marginal character of the basic intrusions. Before the beginning of the updoming the plane of contact between the granite and the overlying sediments was not singularized and could not be expected to display the character of a plane of weakness. Only after the process of updoming had set in, the marginal plane of the granite became a plane of demarcation between two units which reacted in a different way against the deforming forces, and only then it became a plane of weakness predestined to be injected by fused rocks and thus it is extremely unlikely that before the updoming intrusions or injections of magma should have occurred showing now a marginal character. For this reason the writers favour the first-mentioned view that this basic group is a differentiation-product from the parent magma associated with the uplift.

The acid group is later in age and includes the little bosses of alkali-granite, with their suite of nepheline-syenite dykes. Some of the latter are found cutting through the former, while others were intruded into Lower Witwatersrand strata; the writers have elsewhere [1]) suggested the possibility of these nepheline-syenite masses being due to deep-seated assimilations of dolomite, in accordance with the hypothesis of DALY [2]).

c. *Metamorphic Phenomena.* The probable circumstances from which metamorphic rocks resulted were discussed in the final section of Chapter IV. It was there shown that one group of rocks represents the effect of an earlier regional component of metamorphism, and is characterised by minerals of low molecular volume, and that great pressure is the dominant agent — with results distributed concentrically with the Vredefort Granite. Load, i.e. the weight of superincumbent sediments during the pre-Updoming period, may have initiated this type of metamorphism, but it is possible that a special role tending to accentuate such changes must be ascribed to the intense pressure created as a result of Updoming.

The other group of altered rocks is due to the closely associated, though somewhat later local (thermal) component of metamorphism based essentially on heat (in combination with pressure) derived from the emplacement of the major intrusion; andalusite-cordierite-biotite-hornfels is a typical form of this metamorphism. Each phase of the postulate thus has a corresponding metamorphic expression. It is quite possible that the granite itself has been modified under some phase of this metamorphism.

In his account of the Vredefort granite, SHAND [3]) first called attention to the heterogeneous character of that formation near Parijs, specially noting the presence of two elements in it, a gray and a pink one, also referred to in section 1 of Chapter III above. Anyone familiar with the Older Granite as typically developed at Nelspruit, in the Leydsdorp and Pietersburg districts, or between Pretoria and Johannesburg, or again in North-Western Swaziland, knows that it is almost invariably gray, and never red, or — quite exceptionally — due sometimes to younger felspathic veins. The Vredefort Granite often has a pronounced red colour and, as a formation, is not quite like the typical Older Granite. While it certainly has undergone structural changes, explained in a previous section, and resulting from the intense stress to which it was subjected, it is quite

1) G. A. F. MOLENGRAAFF and A. L. HALL, **63**, pp. 485—486.

2) R. A. DALY, **15**.

3) SHAND S. J., **85**.

conceivable that during its peculiar tectonic history it may have undergone metamorphism somehow connected with the younger magma and have been altered ("contaminated") by some elements derived from it. It is difficult to resist the suggestion that the lowermost zones of the granitic plug may have locally reacted with the younger magma in such a manner as to take up some constituents, without having undergone actual fusion to any degree. Such changes probably took place at a considerable depth, prior to the forcing upwards of the resulting "migmatic" Vredefort Granite, since the later crush-phenomena affect both granitic elements indiscriminately. Analogous cases are known where strongly altered sediments, which never became fused, yet contain elements of igneous origin that could scarcely have been introduced otherwise than in a molten condition. In some such manner the abnormal features of the Vredefort Granite may perhaps be accounted for.

D. Igneous Activity of the Bushveld Magmatic Province in relation to that of the Vredefort Province.

Passing reference was made above to the possibility of the cycle of igneous activity of the Bushveld Complex being connected with the igneous and tectonic events just discussed, as two aspects of one major and more widespread activity ; it is desirable to examine this suggestion more fully, for which purpose the reader is presumed to be familiar with at any rate, the leading features of the Bushveld Complex [1]).

In many regions of eruptive rocks it has been found that within the same magmatic cycle the principal igneous events fall into three phases in this order : First or Volcanic Phase, Second or Plutonic Phase, and Third or Phase of Minor Intrusions ; it is, however, important to remember in connection with the subsequent discussion that one or other phase may be reduced or even missing. All the volcanic, intrusive, and tectonic incidents directly or indirectly associated with the Bushveld Complex may be said to fall within the ,,Bushveld Magmatic Province" — thus constituting the "Bushveld Chapter". Similarly, the analogous events within the Vredefort Mountain Land and its central granite may be said to fall within the "Vredefort Magmatic Province" — thus forming the "Vredefort Chapter".

The period of geological events extending from the top of the Pretoria Series to the base of the (true) Waterberg System [2]) also covers an extensive igneous activity, which began soon after the close of the Pretoria Series, gradually increased in intensity and then died down ; this cycle comprised the three main phases alluded to above. The writers suggest that this igneous period — though one grand cycle, embraced two

1) The most recent summary will be found in R. A. Daly and G. A. F. Molengraaff, **16**.

2) i. e. so as to include what was formerly defined as the Lower Waterberg Felsites.

genetically connected chapters, running either parallel, or perhaps more likely overlapping, i.e. the Bushveld Chapter and the Vredefort Chapter.

For the Bushveld Chapter the Volcanic Phase begins [1]) with outpourings of acid lavas on a great scale and leads to a succession of felsites several thousand feet thick — formerly classed as the Lower Waterberg felsite group. The Plutonic Phase embraces the Bushveld Complex proper, i.e. the emplacement of the hypersthene-gabbros, pyroxenites, etc. referred to as the norite group ; this is the earlier set of plutonic intrusions, and is succeeded by the later Red or Bushveld Granite. Though the latter is intrusive in the former, the view that both are partial magmas differentiated from a common magma (as the primary Plutonic phase) is not inconsistent with field relationships, and is supported by the constant association of the two groups. The phase of minor intrusions consists of several small scattered groups of intrusive rocks found outside the main mass of the Bushveld, but composed of types closely allied to the norite and Red Granite divisions. Here belong the little mass of pyroxenitic rocks at Steenkopjes north-west of Krugersdorp, the miniature Bushveld Complex round the Argent Silver Mine on Dwarsfontein, little inliers of Red Granite round Crocodile Pools, the Bushveld offshoot in the Northern Waterberg District, perhaps also certain younger gabbroid rocks within the Heidelberg area, and a few dykes [2]).

In the Vredefort Chapter the Volcanic Phase cannot now be traced, and it may form one of those cases where the initial episode of a major igneous cycle is missing. On the other hand the postulate of the writers may in part represent a potential volcanic phase, which, owing to the superincumbent load, did not result in effusive phenomena. The Plutonic Phase is covered by the emplacement of a magma, still largely concealed. Here one meets with several fairly close analogies with the corresponding episode of the Bushveld Chapter. Thus there is the earlier basic division (marginal interior and exterior intrusions), and, as within the higher beds of the Pretoria Series round the norite group, so round the Vredefort Granite, the Lower Witwatersrand strata are injected by many basic sheets, which also decrease as one ascends in the succession. Then there is the

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1) It might be argued that the basic amygdaloidal lavas found at three horizons in the Pretoria Series (one of which — the Dullstroom Volcanic Series — is in contact with the norite) form part of this Volcanic Phase. Since they closely resemble one another and almost certainly correspond to the Ongeluk Volcanic Series in the Griqua Town Beds of the Cape Province, it is more likely that they have no genetic connection with the Bushveld Chapter, but belong to an earlier period of igneous activity.

2) It is by no means excluded that the Great Dyke of Southern Rhodesia may be another manifestation of the Bushveld period of igneous activity, though situated well away from the main seat of emplacement. This dyke is from two to eight miles wide and persistent over 300 miles; it is made up of rocks very similar to those occupying the basic margin of the Bushveld, i. e. norites, pyroxenites ond peridotite, which sometimes show an orderly distribution within the dyke.

somewhat later acid group represented by the alkali-granite bosses analogous to the Red Granite of the Bushveld. The existence of the third or phase of minor intrusions is doubtful. Certainly the canadites and allied nepheline-bearing rocks of the Witbank area are so closely associated with the alkali-granite bosses that they can scarcely be otherwise than genetically connected with them and of the same period of consolidation. The case is somewhat different, however, with the extensive and powerful dykes which extend from the Vredefort Mountain Land practically without interruption into the Bushveld Complex.

The question now arises what are the features suggesting a genetic connection between the Bushveld and Vredefort Chapters ?

Apart from the fairly close analogies already pointed out, there is the following train of thought. It is unlikely that an igneous event of such magnitude as the Bushveld Complex should have been rigidly confined to a single display of magmatic phenomena, and it is far more likely that subsidiary manifestations would have occurred at scattered points outside the periphery of the Bushveld proper. It is suggested that the little occurrences of Steenkopjes, Dwarsfontein, etc. represent such local extensions of the main magmatic activity. Not only are these admissible geographically, but their interpretation as such is supported by petrographical analogies. Further, the magmatic adjustments below the Vredefort granite — including a portion of the sedimentary girdle — while only a potential volcanic phase as explained above, may likewise not have been geographically restricted, but, as in the case of the Bushveld Complex, shown manifestations similar in principle outside their main seat. If this did occur and e.g. under a much smaller superincumbent load, effusive phenomena may have resulted. It is not excluded that the Pilandsberg illustrates such a case with its more or less circular arrangement of formations. In support of this view, it is interesting to observe that some of the nepheline-syenite dykes extend from the top of the Lower Witwatersrand System in that area northwards across the Magaliesberg and through the norite of the Bushveld into the Pilandsberg (also a region of alkali-rocks), as if they were channels of communication between the two centres of alkali rocks. Since the Pilandsberg is surrounded on all sides by the norite, the Vredefort Chapter would thus appear to be somewhat later in age than the Bushveld Chapter — both probably running concurrently for part of the time.

The preceding discussion may be conveniently tabulated as follows (See Table pag. 172).

These are the features which — while not amounting to a proof — are in the writers' opinion sufficiently numerous and suggestive to admit a genetic connection between the igneous events in the two magmatic provinces as a working hypothesis.

Bushveld-Vredefort Cycle of Igneous Activity.
(One grand magmatic basin).

	Bushveld Chapter. (Earlier main partial magma)	Vredefort Chapter. (Later main partial magma).
Surface Indications.	Well exposed over a large area.	Largely still concealed.
Date.	Post Pretoria Series and pre-Waterberg (formerly Upper Waterberg).	Post Pretoria Series (or post Norite ?) and pre-Waterberg (formerly Upper Waterberg). In part perhaps slightly post-Waterberg.
Main Tectonic Effect.	Sinking of Pretoria Series floor. Many faults in sedimentary periphery. No inversion of succession.	Updoming of Vredefort Granite. Overtilting of Witwatersrand System and Inversion of Succession. Intense pressure, many faults and flinty crush-rocks; a girdle of sediments round circular area of granite.
Volcanic Phase.	Great Suite of Acid Lavas (Lower Waterberg Felsites)	Not traceable; possibly reflected in a symmetrical uplift. Pilandsberg a true volcanic phase ?
Plutonic Phase.	An earlier basic group — Norite and a later acid group — the Bushveld Granite.	Earlier basic marginal intrusions, later alkali-granite, with small dykes of nepheline-syenite.
Main emplacement of the Plutonic Phase.	Over Bushveld area.	Within and under Mountain Land or Vredefort Granite.
The Roof of the Plutonic Phase.	„Lower Waterberg" Felsites and Rooiberg Quartzites.	The Vredefort Granite and sediments from the Witwatersrand System up to the Transvaal System.
Phase of Minor Intrusions.	Small masses outside Bushveld Proper; e. g. Dwarsfontein.	? Extensive Nepheline Syenite dykes extending northwards in the Pilandsberg.
Metamorphic Effects	Essentially thermal; locally complicated by pressure-phenomena, e. g. Malips Drift.	An earlier Regional (Pressure) component concentric with Vredefort Granite; a later local component, excentric, and due to the Plutonic phase.

E. The Post-Updoming Period.

This extends from the close of the Updoming Period with its tectonic and magmatic incidents down to the present time.

It was pointed out that the rocks of the Karroo System show no signs of having suffered under these events, which therefore must have been concluded before that period began. The latter must have been preceded by a long interval during which the updomed Vredefort Granite together with its girdle of tilted sediments was subject to denudation until the Karroo rocks were deposited on an irregular floor of older formations.

Probably — like a great part of South Africa — our area has enjoyed continental conditions since the close of the Karroo System, and has been subjected to the process of erosion, until to-day the major portion is denuded of its Karroo covering. The alternating series of relatively hard and soft rocks of the Witwatersrand System show the effects of the differential rate of erosion and tend to lag behind the more rapidly weathering central granite, until there stands out a striking amphitheatre of ridges surrounding a circular plain of granite, as that remarkable piece of complex and concentrated geology, of which the writers have attempted to give some account in the preceding pages.

Conclusion. The authors realise the great difficulty of writing the main lines of the geological history of their area in such a manner as to meet general approval, but the central idea of centripetal pressure followed by an uplift due to magmatic adjustments appear to coordinate many otherwise isolated igneous and tectonic events. It seems to realise the strikingly circular arrangement of the girdle of sediments, characterised by overtilting and an inversion of the succession. It recognises the same cycle of magmatic events, shown in many other regions of eruptive activity, and throws some light on the factors of metamorphism. It does not appeal to a unique set of causes, but in tying up with analogous phenomena elsewhere it postulates a difference in degree rather than in kind, and thus entails a minimum of speculation. Last, but not least, it tends to establish an essential unity between the magmatic provinces of the Bushveld and the Vredefort area as phases of a single grand igneous chapter.

SUMMARY.

The more important results presented in the preceding pages may be summarized as follows :

1. In the northernmost parts of the Orange Free State lies the *Vredefort Granite* in the form of a circular outcrop, 40 km. in diameter, though a small portion of the circle in the south is covered by younger Karroo rocks. Surrounding the granite-area is a girdle of sediments.

2. This granite is a coarse-grained somewhat gneissic red or grey biotite-granite and assigned to the so-called "Older" Granite of the Transvaal.

3. *A succession of sediments* some 13000 m. in total thickness surrounds the Vredefort Granite and gives rise to a more or less regular amphitheatre of quartzite-ridges. This sedimentary girdle comprises that portion of the geological column which extends from the base of the Witwatersrand System upwards through the Ventersdorp as far as the Gatsrand or Pretoria Series of the Transvaal System, the first named system lying in contact with the margin of the central granite.

4. These *sediments are tilted* and for the greater part *overtilted* and hence dip in many places radially into the granite. The consequent *inversion of the succession* affects in places not less than 10000 m. of sediments from the granite-periphery outwards.

5. Within the granite, but only over its peripheral portions, are a group of basic intrusions (described as *interior basic marginal intrusions*). These run more or less concentrically with the periphery and for the most part form dykes or sill-like bodies composed of gabbros, hyperites, etc. ; they are to a large extent epidioritised. Intrusions of sill-shape locally pass into dyke-like bodies. In one case an interior marginal intrusion has invaded the lowermost sediments and has consolidated as a small boss strongly hybridised through the assimilation of material derived from the invaded granite and quartzites.

6. At the very base of the girdle of sediments, and in direct contact with the granite-margin, lies the *Basal Amygdaloid*, up to about 600 m. in thickness ; this formation is not represented on the Witwatersrand or in the Heidelberg area. Though originating as a contemporaneous basic amygdaloidal lava, the Basal Amygdaloid through metamorphism is epidioritised, and has passed into an amphibolitic rock with granulitic microstructure, which may be termed hornblende-granulite.

7. The belt of country along and within the margin of the sedimentary girdle close to the central granite shows a large number of faults, both radial and peripheral. They are later in age than the period of emplacement of the basic marginal intrusions, though most likely closely associated genetically with the tectonic history that helped to bring about such emplacement.

8. In the lower portion of the Lower Witwatersrand System there is another series of basic intrusions (described as exterior basic marginal intrusions). These rocks are also much epidioritised and in their shape, petrographical, as well as chemical characters present remarkably close affinities to the interior basic marginal intrusions. They are specially abundant along that belt of the sediments lying nearest to the granite-periphery.

9. Both interior and exterior marginal intrusions indicate a community of origin as the earlier basic differentiates from a younger magma, still largely concealed.

10. In the higher portion of the Lower Witwatersrand System, or more or less along the junction between that group and the Upper Witwatersrand System, as well as in the Dolomite Series of the Transvaal are small bosses or stock-like laccoliths of alkali-granite, clearly intrusive into their sedimentary casing. These alkaline rocks are regarded as the later more acid differentiates from the same younger magma, referred to in conclusion No. 9.

11. A group of dykes of nepheline-syenite (canadite, foyaite etc.) occur intimately associated with the bosses of alkali-granite. They are most probably desilicated differentiates of the alkali-granite magma with which they are connected.

12. The Vredefort Granite and the encircling sediments up to and including the Ventersdorp System are cut in an irregular fashion by countless veins of a black rock known as pseudo-tachylyte, representing the manifestations of the final episode in the tectonic history of the area. This pseudo-tachylyte is not a true igneous rock, but a flinty crush-rock, the result of intense compression, trituration and consequent local fusion of different rocks. Although the veins of pseudo-tachylyte intersect all the other formations, both igneous and sedimentary, indiscriminately they do not occur in the dykes of enstatite-granophyre.

13. Restricted to the contact-belt between granite and sediments dykes of a peculiar apparently true igneous rock, enstatite-granophyre, occur. Their course, concentric with, or slightly oblique to, the granite-periphery, recalls that of ring-dykes. Their most characteristic feature is the extraordinary number of xenoliths of crushed quartzite, derived from the quartzites of the lowest Witwatersrand beds. Their complete freedom from veins of flinty crush-rock is not regarded as accidental, but as having

genetic significance, suggesting, together with a certain resemblance between enstatite-granophyre and pseudo-tachylyte, the possibility that the former has to be regarded as a flinty crush-rock on a gigantic scale originating from ultra-trituration and partial fusion of different rocks.

14. Profound Metamorphism has affected the girdle of sediments and in places its results are traceable through the entire thickness of the Lower Witwatersrand System (3000 m.). In their area of maximum development the altered rocks have a surface width of 6.5 km. from the granite-margin outwards.

15. The non-intrusive character of this granite is based on the absence of apophyses, on the absence of endomorphic modifications along the margin of the granite, and on the fact that the scale of the metamorphic phenomena is out of all proportion.

16. The principal metamorphic rocks are: Cordierite-biotite-hornfels, andalusite-biotite-hornfels, with or without garnet, garnet-actinolite-hornfels etc. All these types are thoroughly recrystallised and locally exceptionally coarse.

17. The metamorphic province of the Vredefort Mountain Land constitutes an example of Polymetamorphism in two successive components, some parts of the metamorphic province having been subjected to one or other of these components, other parts to both (superposed metamorphism).

18. The earlier component is Regional, the essential agent being static pressure (with cooperation of heat).

19. Its effects are distributed concentrically so as to form a narrow ring of hornblende-granulite (Basal Amygdaloid), garnet-amphibole-hornfels (Water Tower Slates) etc. round the central granite.

20. Its cause is primarily the load of superincumbent strata (3500 atmospheres) aided by heat (400° C.), perhaps in combination with orogenic forces during the updoming of the granite.

21. The later component is Local, the essential agent being heat (with cooperation of pressure).

22. Its effects are distributed excentrically with reference to the granite-circle and form an irregular area of cordierite-biotite-hornfels, andalusite-biotite-hornfels etc. up to 6.5 km. wide, occupying the northern, north-western and western parts of the girdle of sediments.

23. Its cause was the emplacement of a large younger intrusion, to a great extent concealed, though exposed as three small bosses of alkali-granite, basic marginal intrusions in the granite, etc.

24. Superposition of the Regional and Local Components occurred along the segment stretching from about Leeuwdoorns on the west to somewhere near Brakfontein on the east. It tends to produce a reinforced metamorphism, indicated by coarser recrystallisation and increased size and abundance of some of the metamorphic minerals.

25. Evidence of P r e s s u r e of almost incredible intensity is provided by the inversion of 6000—10000 m. of the succession, by many faults, by the extraordinary profusion of flinty crush-rocks etc. In this diastrophism the contact-zone between the central granite and its girdle of sediments is an effective plane of weakness, as reflected e.g. in the distribution of the marginal intrusions, enstatite-granophyre dykes, etc.

26. The U p d o m i n g o f t h e c e n t r a l g r a n i t e and its sedimentary cover is the most striking chapter in the tectonic history. Its initial causes are not definitely traceable. It is suggested that this Updoming was initiated by centripetal pressure. The relief of load resulting from this movement caused a y o u n g e r m a g m a b e l o w t h e g r a n i t e t o b e c o m e a c t i v e a n d t o r i s e and thus to assist the updoming and the upward movement of the much heated but passive granite.

27. This updoming calls into play exceptionally powerful pressure, the intensity of which was most likely progressive and at its climax caused a general condition of potential collapse of the crust; this culminating phase constitutes the last or enstatite-granophyre and pseudo-tachylyte stage in the tectonic history.

28. The Vredefort Mountain Land in its relation to the updomed central granite invites comparison, and furnishes certain remarkable analogies, with the B l a c k H i l l s D o m e, D a k o t a, and the R i e s i n B a v a r i a. Some of the differences, e.g. the absence of volcanic rocks in the Vredefort area, are no doubt due to the much greater thickness of the sedimentary prism involved.

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Fig. 1. Granite on Rietpoort.
G. A. F. MOLENGRAAFF PHOT.

Fig. 2. Outcrop of granite on Rietpoort.
L. T. NEL PHOT.

PLATE II.

PLATE II.

Fig. 1.

Ridge of Government Reef Quartzites on Mooiplaats seen from the corner-beacon between the farms Witklipfontein, Sweet Home, Deelfontein and Mooiplaats; behind it in the background the main ridge of Hospital Hill Quartzites.

Fig. 2.

Outcrop of Basal Amygdaloid on Rietpoort. The boulders show amygdules of varying size and shape.

Fig. 1.

G. A. F. MOLENGRAAFF PHOT.

Fig. 2.

L. T. NEL PHOT.

PLATE III.

PLATE III.

Fig. 1.

Baviaanspoort on Witbank, in which the Vaal River cuts the main ridge of Upper Hospital Hill or Green Quartzites. The position of the strata is nearly vertical. In the gap the river forms rapids.

Fig. 2.

Dip-slope of Upper Hospital Hill Quartzites in the Baviaans-krans on Witbank. To the left a well-marked shoulder of hornfels. The Lower Hospital Hill Quartzites crop out on this shoulder at the left end of the darker wooded patch.

Fig. 1.

F. E. WRIGHT PHOT.

Fig. 2.

F. E. WRIGHT PHOT.

PLATE IV.

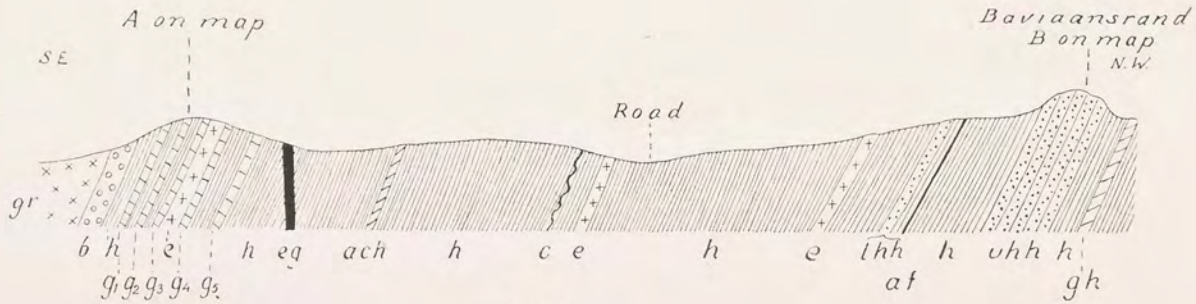
PLATE IV.

Fig. 1.

Section across lower portion of the Lower Witwatersrand Beds on Witbank. Length of section approx. 2.5 km. *gr.* granite, *b.* Basal Amygdaloid, g_1—g_5 Orange Grove Quartzites, at the base of the metamorphosed ferruginous slates or Water Tower Slates, *ach.* andalusite-cordierite-hornfels, *c.* contorted ferruginous band, *h.* hornfels, *lhh.* Lower Hospital Hill Quartzites, *af.* actinolite-fels, *uhh.* Upper Hospital Quartzites, *gh.* garnet-hornfels, *e.* epidiorite, *eg.* Enstatite Granophyre.

Fig. 2.

Section across lower portion of the Lower Witwatersrand Beds on Rietpoort. Length of Section approx. 2 km. *gr.* granite, *b.* Basal Amygdaloid, g_1—g_5 Orange Grove Quartzites, *h.* hornfels, *sb.* speckled bed, *lhh.* Lower Hospital Hill Quartzites, *uhh.* Upper Hospital Hill Quartzites, *af.* actinolite-fels, *e.* epidiorite, *eg.* enstatite-granophyre, *bl.* block of hornfels in Basal Amygdaloid.


A on map
SE
Baviaansrand
B on map
N.W.
Road
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b h e h eq ach h c e h e lhh h uhh h
g1 g2 g3 g4 g5
at
gh

Fig. 1.

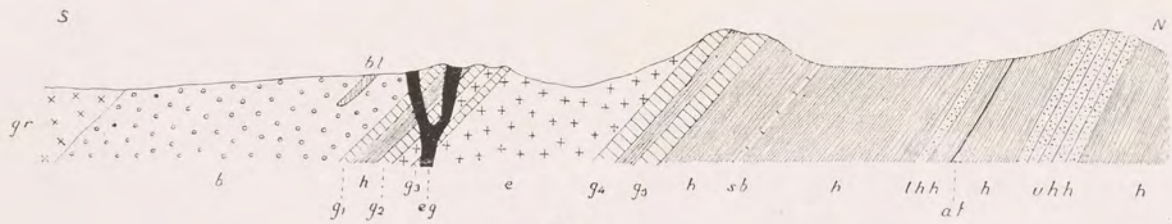
S
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Fig. 2.

PLATE V.

PLATE V.

Fig. 1.

The Baviaanskrans, a ridge composed of the Upper Hospital Hill Quartzites, showing the gap (Baviaanspoort) through which the Vaal River flows, seen from a hill in the granite-area. In the foreground one of the marginal epidioritised gabbro-kopjes. Beyond the gap in the distance the range of Main-Bird Reef Quartzites.

Fig. 2.

To the left the ridge of Orange Grove Quartzites on Rietpoort, strongly overtilted and dipping towards the granite, to the right the area of the Vredefort Granite with its encircling girdle of sediments faintly indicated in the background; in the middle one of the marginal basic intrusions known as the Twin-kopjes, composed of epidioritised gabbro.

Fig. 1.

G. A. F. MOLENGRAAFF PHOT.

Fig. 2.

L. T. NEL PHOT.

Fig. 1. Liebenberg kopje on Rietpoort near the Vaal River.
Olivine-gabbro.

G. A. F. MOLENGRAAFF PHOT.

Fig. 2. Joints in a marginal sill of gabbro in Vredefort Granite
on Anna's Rust.

A. L. HALL PHOT.

PLATE VII.

PLATE VII.

Fig. 1.

Hybridised gabbro with much micropegmatite, Tweefontein. Magn. 31 ×, Crossed Nicols.

Fig. 2.

Micropegmatite growing out from first generation of basic plagioclase. Threadlike myrmekitic micropegmatite passes into coarser micropegmatite. Hybridised gabbro, Tweefontein. Magn. 14 ×.

Fig. 3.

Micropegmatite growing out from second generation of acid plagioclase. Hybridised gabbro, Tweefontein. Magn. 42 ×, Crossed Nicols

Fig. 4.

Myrmekite growing out from second generation of acid plagioclase and passing into micropegmatite. Hybridised gabbro, Tweefontein. Magn. 87 ×, Crossed Nicols.

Fig. 1.

Fig. 2.

Fig. 3.

Fig. 4.

P. KRUIZINGA PHOT.

PLATE VIII.

PLATE VIII.

Fig. 1.

Xenolith of quartzite (white) surrounded by rim of amphibole, and micropegmatite in hybridised gabbro, Tweefontein. Magn. 31 ×.

Fig. 2.

Advanced stage of epidioritisation of gabbro. A group of crystals of actinolite is cut at right angles to the axis c. Big sill on Rietpoort. Magn. 70 ×, Crossed Nicols.

Fig. 3.

Advanced stage of epidioritisation of gabbro in a big sill on Rietpoort. Vigorous growth of prisms of actinolite in clear areas. Magn. 30 ×, Crossed Nicols.

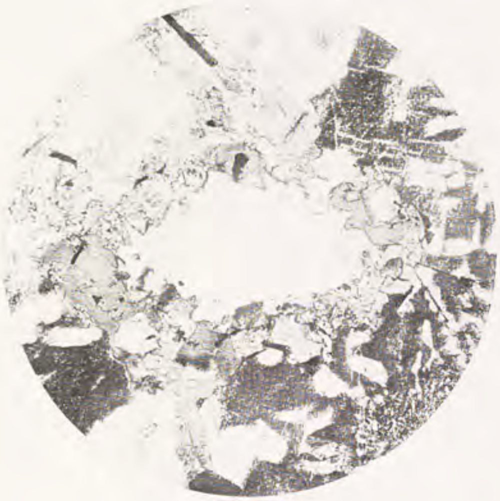


Fig. 1.

Fig. 2.

Fig. 3.

P. KRUIZINGA PHOT.

PLATE IX.

PLATE IX.

Fig. 1.

The main dyke of enstatite-granophyre cuts through the lowermost bar of the Orange Grove Quartzites on Rietpoort.
To the left enstatite-granophyre (black), to the right Orange Grove Quartzite (white).

Fig. 2.

Xenoliths of quartzite, granite etc. protruding from weathered surface of enstatite-granophyre on Rietpoort.

Fig. 1.

A. L. HALL PHOT.

Fig. 2.

A. W. ROGERS PHOT.

PLATE X.

PLATE X.

Fig. 1.

Micropegmatite structures growing out from crystals of plagioclase in enstatite-granophyre. The micropegmatite in places resembles myrmekite. Rietkuil. Magn. 70 ×, Crossed Nicols.

Fig. 2.

Large units of micropegmatite (light-coloured) in enstatite-granophyre, Witbank. Magn. 25 ×, Crossed Nicols.

Fig. 3.

Contact between enstatite-granophyre, and a xenolith of crushed quartzite, Witbank. *e.g.* enstatite-granophyre, *q.* quartzite. Magn. 42 ×, Crossed Nicols.

Fig. 4.

Spherulites of rhombic pyroxene in an apophysis of enstatite-granophyre in granite on Kopjeskraal. Magn. 42 ×.

Fig. 1.

Fig. 2.

Fig. 3.

Fig. 4.

P. KRUIZINGA PHOT.

PLATE X.

Fig. 1.

Micropegmatite structures growing out from crystals of plagioclase in enstatite-granophyre. The micropegmatite in places resembles myrmekite. Rietkuil. Magn. 70 ×, Crossed Nicols.

Fig. 2.

Large units of micropegmatite (light-coloured) in enstatite-granophyre, Witbank. Magn. 25 ×, Crossed Nicols.

Fig. 3.

Contact between enstatite-granophyre, and a xenolith of crushed quartzite, Witbank. *e.g.* enstatite-granophyre, *q.* quartzite. Magn. 42 ×, Crossed Nicols.

Fig. 4.

Spherulites of rhombic pyroxene in an apophysis of enstatite-granophyre in granite on Kopjeskraal. Magn. 42 ×.

Fig. 2.

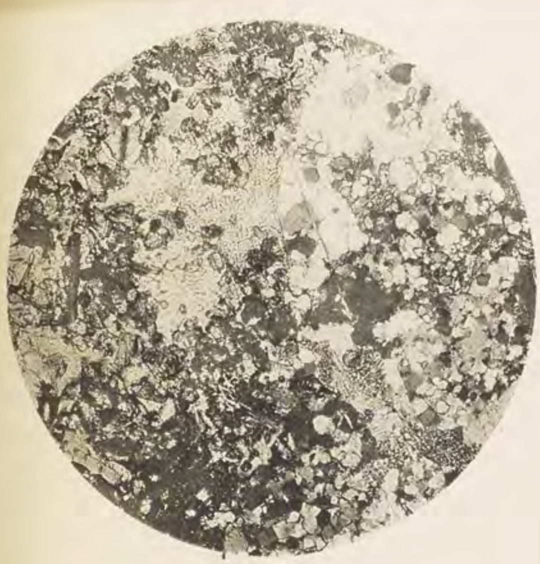


Fig. 3.

Fig. 4.

P. KRUIZINGA PHOT.

PLATE XI.

PLATE XI.

Fig. 1.

The faulted area on Witbank seen from the top of the main ridge of Upper Hospital Quartzites on Kopjeskraal. 1. Vredefort Granite, 2. Orange Grove Quartzites, 3. Marginal intrusion of epidioritised gabbro in granite (compare Pl. V fig. 1), 4. Lower Hospital Hill Quartzites, 5. Upper Hospital Hill Quartzites, *F*. Faults.

Fig. 2.

Micro-fault in nepheline-syenite (Canadite), Dyke 1 on Witbank.
a. albite, *m*. microcline, *n*. nepheline. Magn. 71 ×, Crossed Nicols.

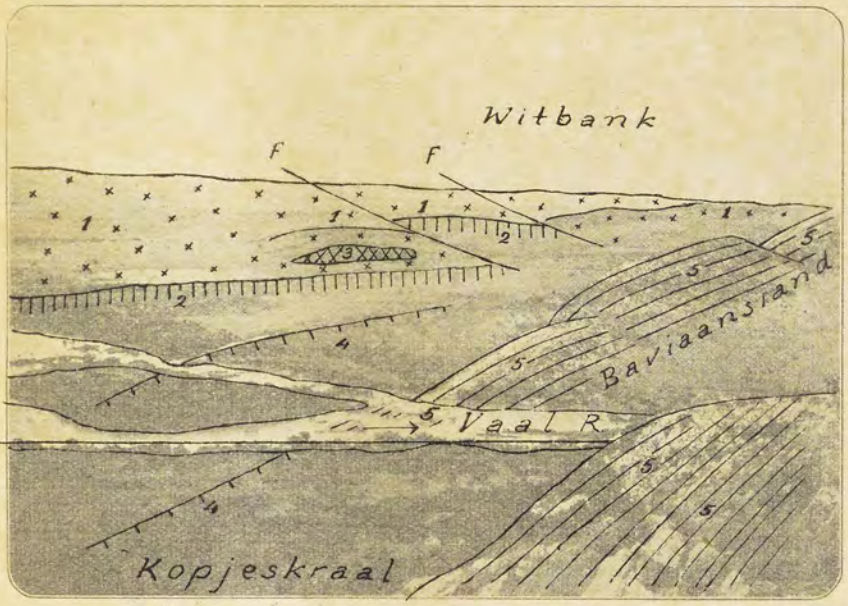


Fig. 1.

G. A. F. MOLENGRAAFF PHOT.

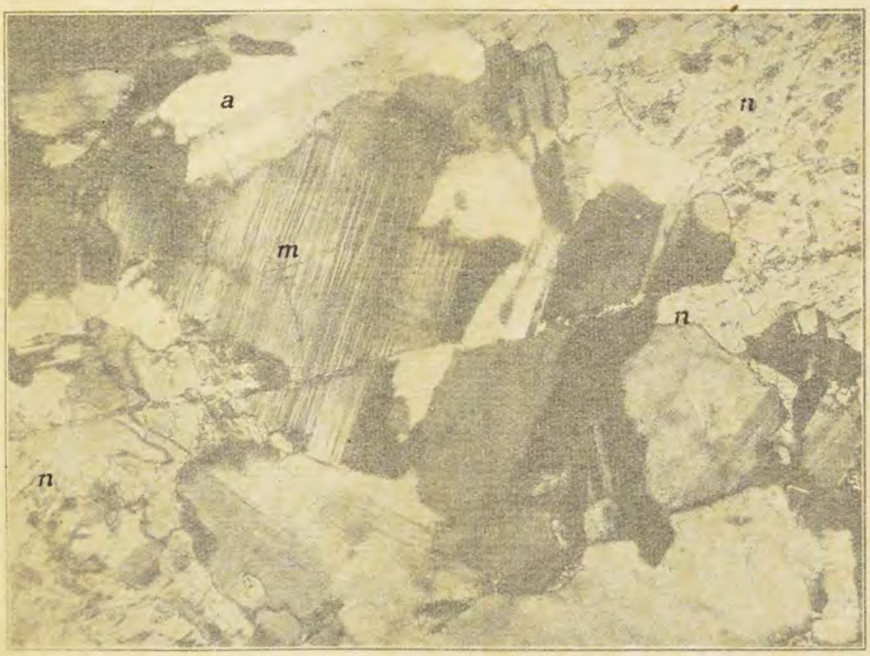


Fig. 2.

P. KRUIZINGA PHOT.

PLATE XI.

Fig. 1.

The faulted area on Witbank seen from the top of the main ridge of Upper Hospital Quartzites on Kopjeskraal. 1. Vredefort Granite, 2. Orange Grove Quartzites, 3. Marginal intrusion of epidioritised gabbro in granite (compare Pl. V fig. 1), 4. Lower Hospital Hill Quartzites, 5. Upper Hospital Hill Quartzites, *F.* Faults.

Fig. 2.

Micro-fault in nepheline-syenite (Canadite). Dyke 1 on Witbank.

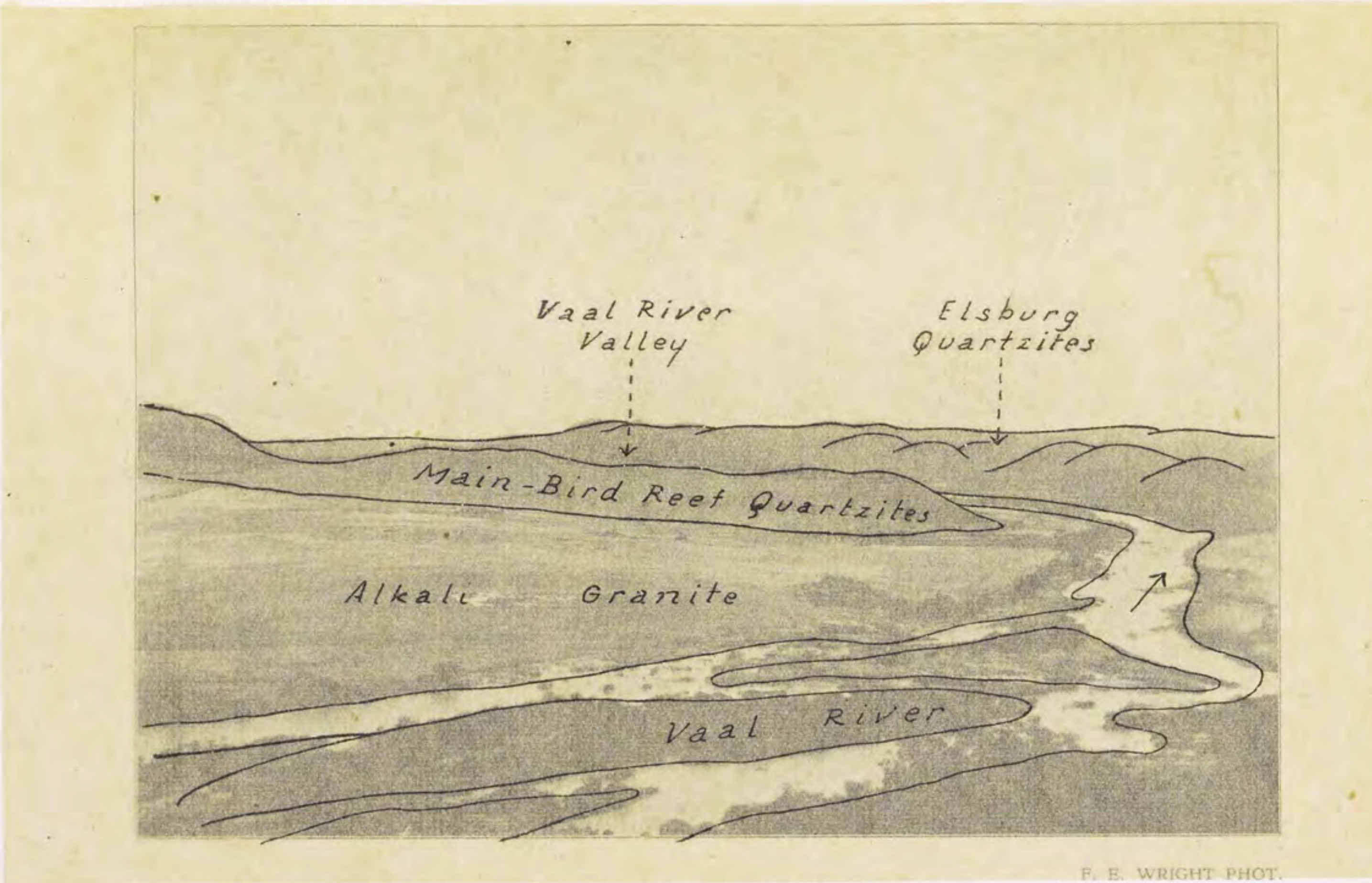
a. albite, *m.* microcline, *n.* nepheline. Magn. 71 ×, Crossed Nicols.

Fig. 1.

G. A. F. MOLENGRAAFF PHOT.

Fig. 2.

P. KRUIZINGA PHOT.



Geological position of the south-western portion of the second boss of alkali-granite on the farm Schurvedraai, seen from south-east. To be compared with sketch-map Pl. XXXIX.

F. E. WRIGHT PHOT.

Geological position of the south-western portion of the second boss of alkali-granite on the farm Schurvedraai, seen from south-east. To be compared with sketch-map Pl. XXXIX.

PLATE XIII.

PLATE XIII.

Fig. 1.

Porphyritic variety of Canadite with large phenocrysts of nepheline (*n*) and anorthoclase (*a*). Dyke 3 on Schurvedraai. Natural Size.

Fig. 2.

Weathered surface of Canadite showing nepheline (*n*) in pits surrounded by rims composed of aegirine and felspar. Dyke 4 on Koedoeslaagte. Natural Size.

Fig. 1.

Fig. 2.

PHOTO GEOL. LAB. DELFT.

PLATE XIV.

PLATE XIV.

Weathered surface of nepheline-syenite. Koedoeslaagte. *an*. anorthoclase, *ae*. aegirine, *n*. nepheline. Natural size.

PHOTO GEOL. LAB. DELFT.

PLATE XV.

PLATE XV.

Fig. 1.

Parallel arrangement of the composing minerals in a canadite of dyke 7; much albite in lath-shaped twin-crystals, somewhat less aegirine and a little nepheline in rounded grains. Magn. 42 ×, Crossed Nicols.

Fig. 2.

Section of a crystal of nepheline parallel to the basal pinacoid showing needles of aegirine arranged parallel to the faces of the prism. Dyke 7, on Koedoeslaagte. Magn. 148 ×.

Fig. 3.

Section of a crystal of nepheline parallel to the vertical axis, showing zonal arrangement of needles of aegirine. Dyke 7, on Koedoeslaagte. Magn. 148 ×.

Fig. 1.

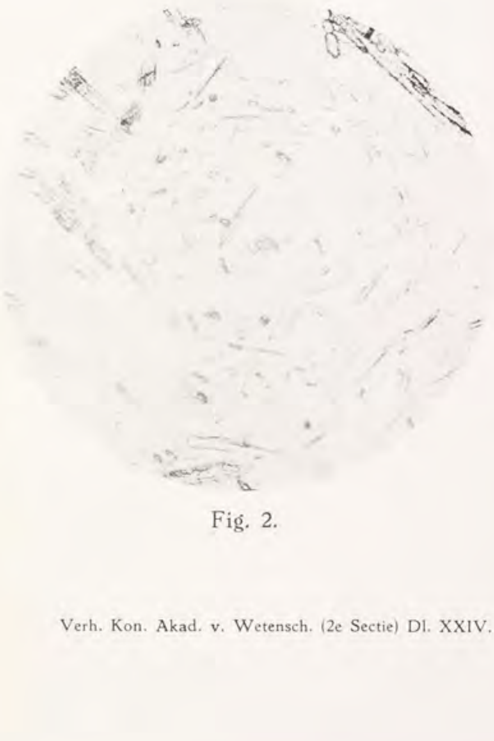


Fig. 2.

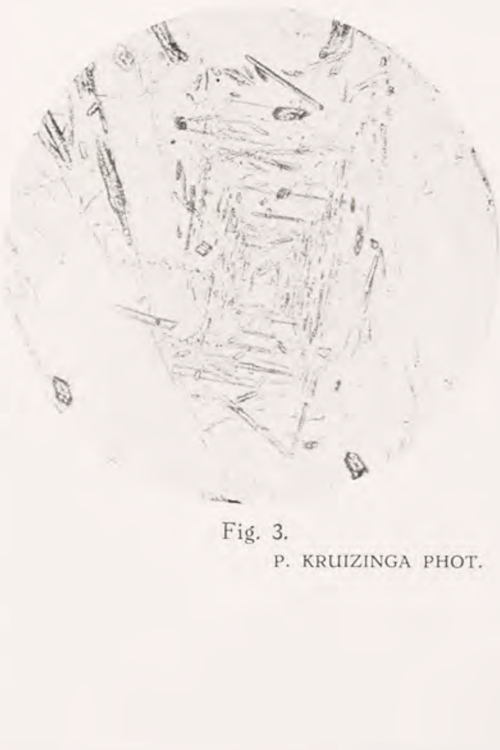


Fig. 3.

P. KRUIZINGA PHOT.

PLATE XVI.

PLATE XVI.

Fig. 1.

Big xenolith of quartzite in hybridised gabbro. Tweefontein. $^1/_{10}$ of Natural Size.

Fig. 2.

Vein of pseudo-tachylyte in porphyritic variety of canadite; *n*. nepheline, enclosing crystals of albite. Dyke 5 on Koedoeslaagte. Magn. 25 ×. Crossed Nicols.

Fig. 3.

Cancrinite-canadite; *c*. cancrinite, *n*. nepheline. Dyke 7 on Koedoeslaagte. Magn. 70 ×. Crossed Nicols.

Fig. 1.
G. A. F. MOLENGRAAFF PHOT.

Fig. 2.

Fig. 3.

P. KRUIZINGA PHOT.

PLATE XVII.

PLATE XVII.

Fig. 1.

Canadite with narrow crush-zones; crystals of albite bent and broken. Koedoeslaagte. Magn. 70 ×, Crossed Nicols.

Fig. 2.

Crush-zone in Canadite, in which the rock is completely pulverised. Near the crush-zone the crystals of albite show a complicated system of delicate micro-step-faults. Koedoeslaagte. Magn. 42 ×, Crossed Nicols.

Fig. 1.

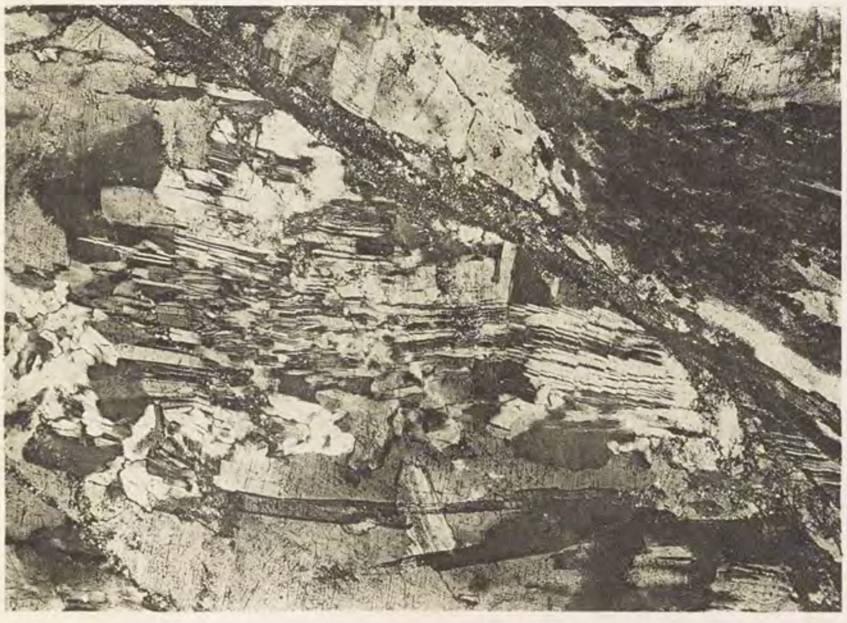


Fig. 2.

P. KRUIZINGA PHOT.

Fig. 1. Veins of pseudo-tachylyte in Kimberley-Elsburg Quartzite. Koedoeslaagte.

L. T. NEL PHOT.

Fig. 2. Network of veinlets of pseudo-tachylyte in block of gabbrodiabase. Twinkopjes, Rietpoort East.

L. T. NEL PHOT.

PLATE XIX.

PLATE XIX.

Fig. 1.

Crush-zones in Canadite, in which the rock is mylonised and triturated, pass into pseudo-tachylyte (black). Koedoeslaagte. Magn. 20 ×, Crossed Nicols.

Fig. 2.

Schistose, sheared and mylonised gabbro with patches of pseudo-tachylyte (black), in which fragments of the crushed rock are enclosed. Twinkopjes on Rietpoort. Magn. 14 ×.

Fig. 1.

Fig. 2.

P. KRUIZINGA PHOT.

PLATE XX.

PLATE XX.

Fig. 1.

Corroded fragments of crushed granite (felspar and quartz) enclosed in pseudo-tachylyte (dark-coloured). Vein in granite, Parijs. Magn. 31 ×, Crossed Nicols.

Fig. 2.

Inclusions of corroded fragments of crushed granite in pseudo-tachylyte. In the middle a large crystal of plagioclase. Vein in granite, Parijs, Magn. 20 ×. Nicols not completely crossed.

Fig. 1.

Fig. 2.

P. KRUIZINGA PHOT.

PLATE XXI.

PLATE XXI.

Fig. 1.

Cracks, crush-zones and patches of pseudo-tachylyte (black) in a gabbro on Kafferkop south-south-west of Parijs. Magn. 6 ×.

Fig. 2.

Flow-structure in pseudo-tachylyte (upper portion). Vein in Ventersdorp Amygdaloid, Buffelshoek No. 629. Magn, 12 ×.

Fig. 3.

Cracked and corroded grain of Government Reef Quartzite in pseudo-tachylyte (black), on Witbank. Magn. 31 ×. Crossed Nicols.

Fig. 1.
P. KRUIZINGA PHOT.

Fig. 2.
L. T. NEL PHOT.

Fig. 3.
P. KRUIZINGA PHOT.

PLATE XXII.

PLATE XXII.

Fig. 1.

Vein of pseudo-tachylyte (black with numerous small inclusions), with apophysis in crushed and partly mylonised epidioritised diabase, on Brakfontein. Magn. 17 ×.

Fig. 2.

Crushed quartzite of Main-Bird Reef Series on Goede Hoop. Rims of triturated quartz visible between the quartz-grains. Magn. 15 ×.

Fig. 3.

Crushed quartzite. Same slide as fig. 2, Crossed Nicols. It is now visible that the quartz-grains themselves are crushed and altered into a mosaic.

Fig. 1.

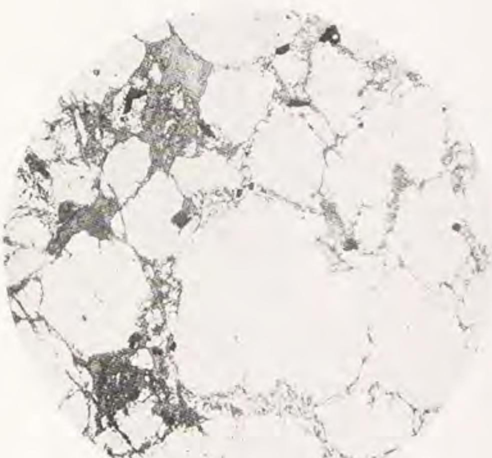


Fig. 1.

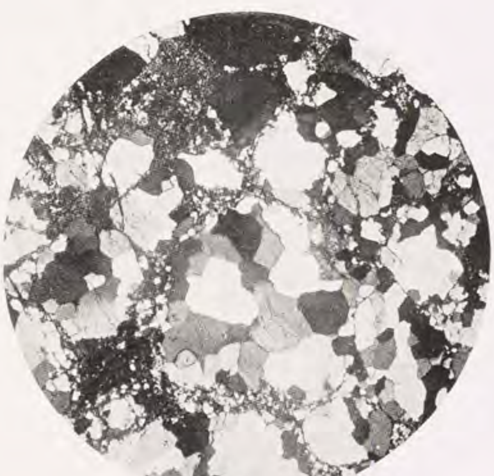


Fig. 2.

P. KRUIZINGA PHOT.

PLATE XXIII.

PLATE XXIII.

Fig. 1.

Crushed and disintegrated granite in the act of being taken up in the pseudo-tachylyte. Koppiesfontein. Magn. 23 ×.

Fig. 2.

Embayment of pseudo-tachylyte in a crushed and disintegrated epidioritised gabbro, Groot Eiland. Fragments of the gabbro are seen floating in the pseudo-tachylyte. Magn. 30 ×.

Fig. 1.

Fig. 2.

P. KRUIZINGA PHOT.

PLATE XXIV.

PLATE XXIV.

Fig. 1.

Pseudo-tachylyte with well-developed spherulitic texture enclosing crushed quartz-grains. Vein in granite on Zijferfontein. Magn. 70 ×. Crossed Nicols.

Fig. 2.

Amphibole-garnet-hornfels. Actinolitic amphibole, garnet and quartz. Baviaanskrans on Witbank. Magn. 28 ×.

Fig. 3.

Vein of pseudo-tachylyte (black) in garnet-hornfels on Koppieskraal. Enclosed in the pseudo-tachylyte xenoliths of crushed quartzite. The black spots in the hornfels are crystals of garnet. Magn. 31 ×. Crossed Nicols.

Fig. 1.

P. KRUIZINGA PHOT.

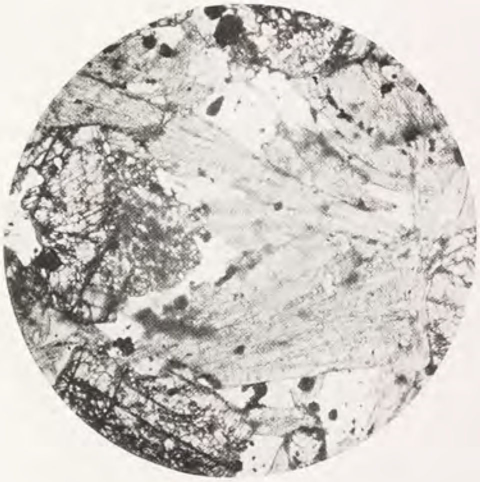


Fig. 2.

A. L. HALL PHOT.

Fig. 3.

P. KRUIZINGA PHOT.

PLATE XXV.

PLATE XXV.

Fig. 1.

Junction between pseudo-tachylyte (dark-coloured area) and crushed and shattered Government Reef Quartzite, Witbank. The pseudo-tachylyte penetrates into the crushed and partly triturated quartzite forming a complicated network in it. Magn. 20 ×, Crossed Nicols.

Fig. 2.

Cordierite-biotite-garnet-hornfels between Lower and Upper Hospital Hill Quartzites on Kopjeskraal. Near one of the short edges is a grain of garnet enclosed between cordierite and biotite. Another grain of garnet touches one of the long edges of the print. At the other short edge is a magnificent area of cordierite with many inclusions of ottrelite in contact with a large flake of biotite. Magn. 30 ×.

Fig. 1.

P. KRUIZINGA PHOT.

Fig. 2.

A. L. HALL PHOT.

PLATE XXVI.

PLATE XXVI.

Fig. 1.

Biotite-cordierite-hornfels from Leeuwdoorns. The lighter coloured portions are cordierite with inclusions of very small needles of ottrelite. The large dark areas are biotite with typical sieve-structure due to quartz. Magn. 11 ×.

Fig. 2.

Amphibole-hornfels between Upper and Lower Hospital Hill Quartzite, Rietkuil-Deelfontein boundary. Felted rosette-like amphibole-aggregates, and quartz. Magn. 28 ×.

Fig. 3.

Xenolith of Jeppestown Slate caught up in alkali-granite, Schurvedraai. Biotite passing into sillimanite, and quartz. Magn. 60 ×.

Fig. 1.

Fig. 2.

Fig. 3.

A. L. HALL PHOT.

PLATE XXVII.

PLATE XXVII.

Fig. 1.

Rosettes of grunerite in magnetite. Hornfels in upper portion of the Lower Witwatersrand Beds on Deelfontein. Magn. 33 ×.

Fig. 2.

Interlocking crystals of quartz in recrystallized Orange Grove Quartzite on Rietpoort. Magn. 28 ×, Crossed Nicols.

Fig. 3.

Andalusite-cordierite-biotite-hornfels on Rhenosterpoort. Along the upper edge a large crystal of andalusite (a) with perfect sieve-structure; in the middle a large flake of biotite showing pleochroic halos and sieve-structure; magnetite (black); in the right corner below some cordierite; the groundmass consists of quartz and biotite, largely altered into chlorite. Magn. 22 ×, Parallel Nicols.

Fig. 4.

Sieve-structure in andalusite-biotite-hornfels on Rhenosterpoort. Large crystals of magnetite and biotite. Magn. 31 ×.

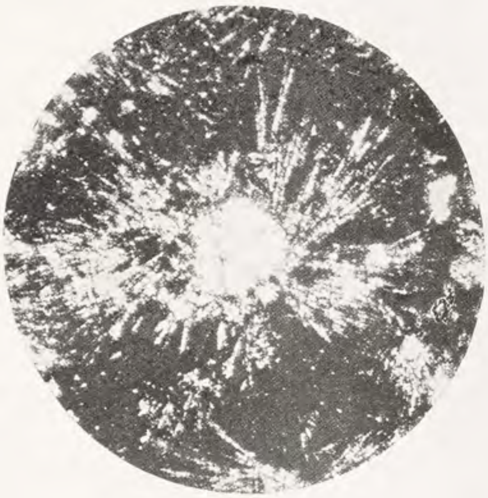


Fig. 1.

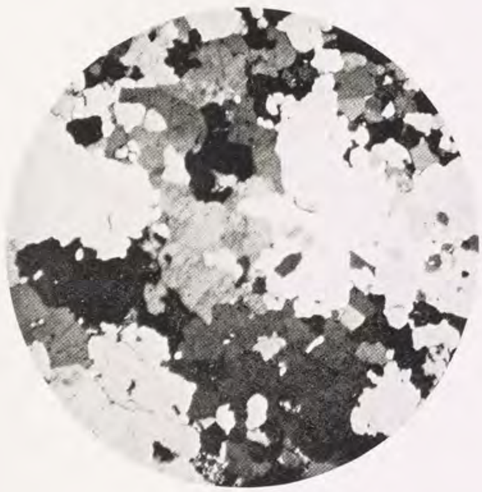


Fig. 2.

A. L. HALL PHOT.

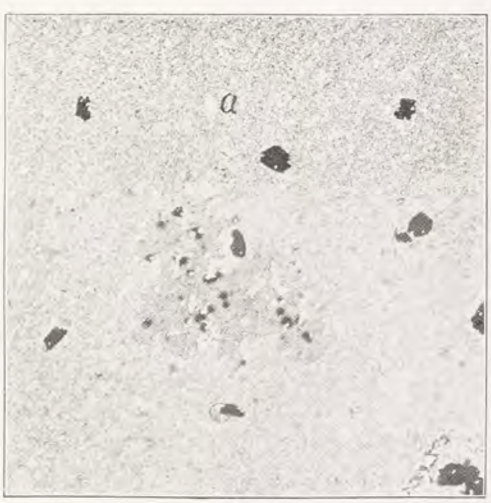


Fig. 3.

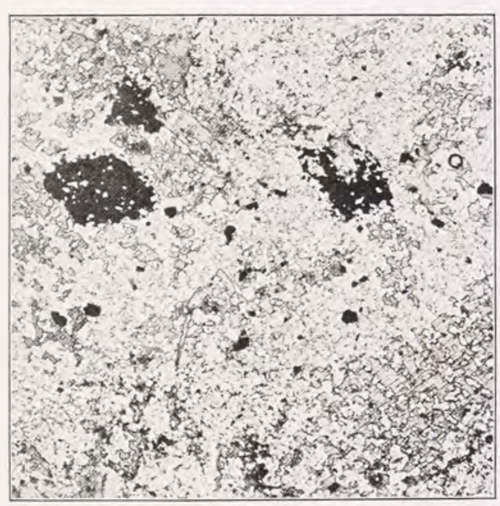


Fig. 4.

P. KRUIZINGA PHOT.

PLATE XXVIII.

PLATE XXVIII.

Fig. 1.

Cordierite-biotite-hornfels on Rietpoort. Along upper edge cordierite with inclusions of ottrelite. Much biotite with sieve-structure and pleochroic halos. Also much quartz in clear areas. Magn. 60 ×, Parallel Nicols.

Fig. 2.

Andalusite-cordierite-biotite-hornfels. Rietpoort. Along lower edge a large plate of andalusite with a cloudy interior but fresh portions left along its margin. It is in contact with a large plate of cordierite full of ottrelite. The same crystal of cordierite is also in contact with a long almost rectangular plate of biotite. Along the contact there are many dark needles of ottrelite. Magn. 30 ×, Parallel Nicols.

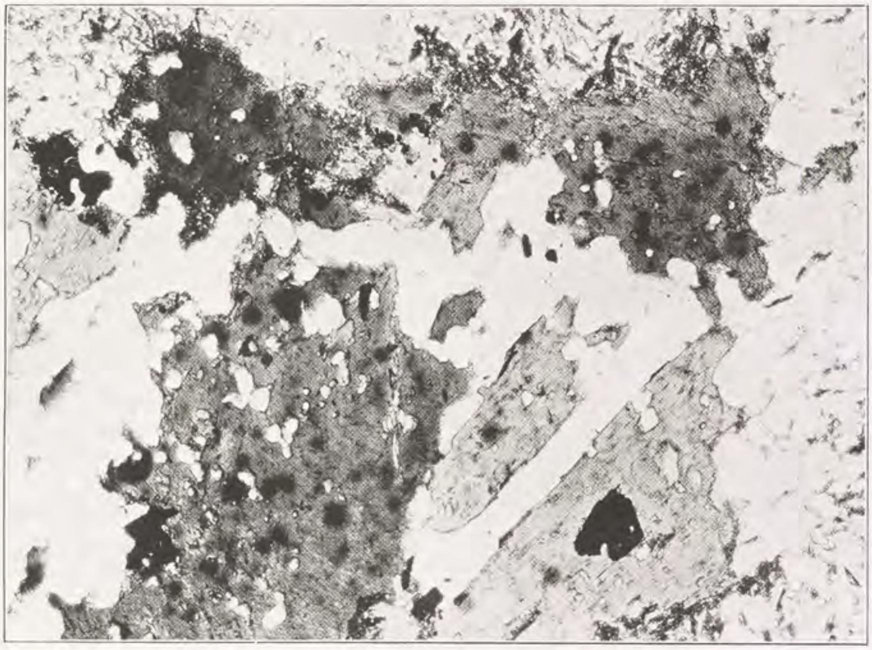


Fig. 1.

Fig. 2.

A. L. HALL PHOT.

PLATE XXIX.

PLATE XXIX.

Fig. 1.

Andalusite-cordierite-biotite-hornfels. Rietpoort.
The andalusite is seen in one small crystal with highly indented outlines near the upper edge; opposite to it is a large crystal of cordierite; running across the middle is a broad band of biotite very higly riddled with inclusions of quartz. Magn. 28 ×.

Fig. 2.

Cordierite-hornfels, Hospital Hill Series on Witbank. Cordierite in large circular areas, biotite, ottrelite, quartz. Magn. 11 ×.

Fig. 3.

Garnet-hornfels from a ledge causing a small waterfall in the Vaal River just below the Baviaanspoort. Garnet with sieve-structure, amphibole, magnetite, quartz.
Magn. 28 ×.

Fig. 4.

Garnet-hornfels, Water Tower Slates, Leeuwdoorns. Garnet, amphibole and quartz. Magn. 33 ×.

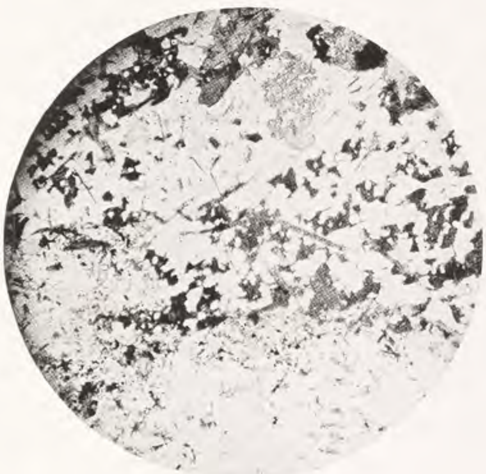


Fig. 1.

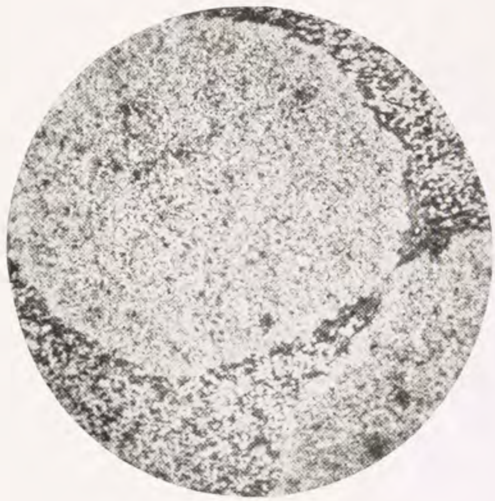


Fig. 2.

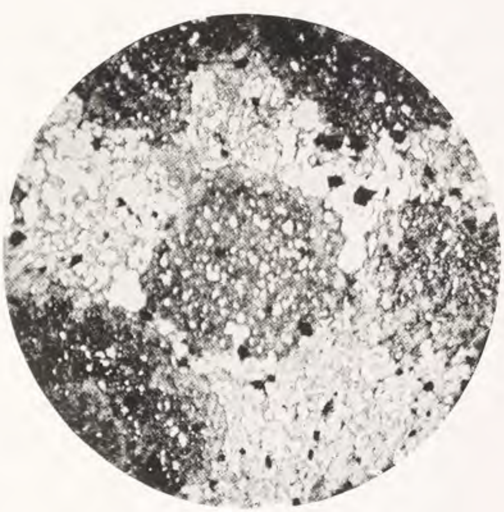


Fig. 3.

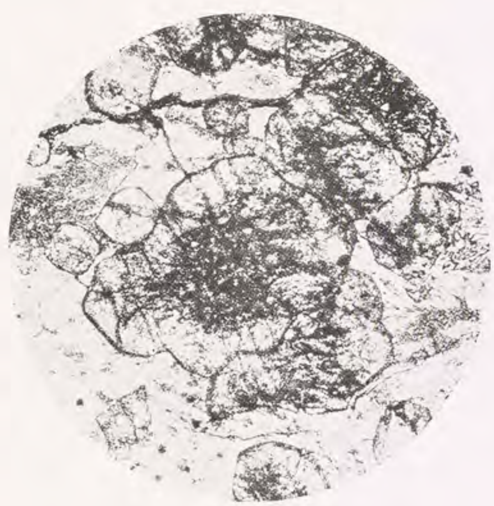


Fig. 4.

A. L. HALL PHOT.

PLATE XXX.

PLATE XXX.

Fig. 1.

Andalusite-cordierite-garnet-hornfels, Hospital Hill Series, Rietpoort. Garnet with exterior borders. There is no andalusite at the spot photographed, but it occurs elsewhere in this slide. Magn. 28 ×.

Fig. 2.

Garnet-hornfels, Water Tower Slates, Brakfontein. Garnet with cloudy interiors; amphibole. Magn. 11 ×.

Fig. 3.

Andalusite-cordierite-biotite-hornfels, Rietpoort. The broad band shaped like an elbow is biotite. Between the elbow and the circumference lies cordierite with inclusions of ottrelite. On the other side of the elbow lies biotite (black) and andalusite (grey). Between the two last named minerals lies a border of clear quartz. At the left edge another cordierite is included between the elbow and the dark plate of biotite. Magn. 28 ×.

Fig. 4.

Sheaves of hornblende in garnet-amphibole-hornfels, Water Tower Slates, Rietpoort. Besides amphibole also magnetite and quartz. Magn. 28 ×.

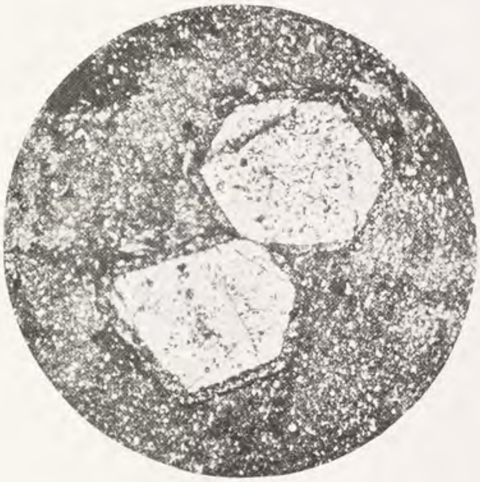


Fig. 1.

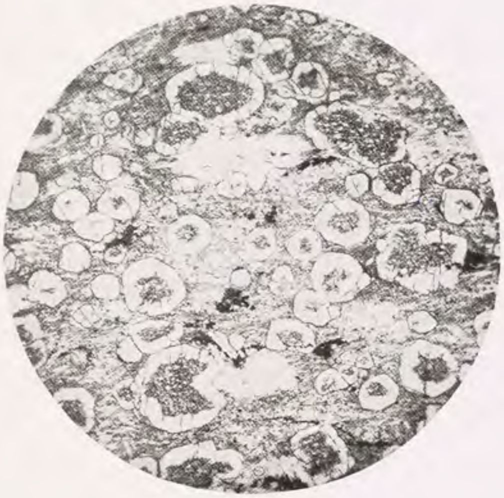


Fig. 2.

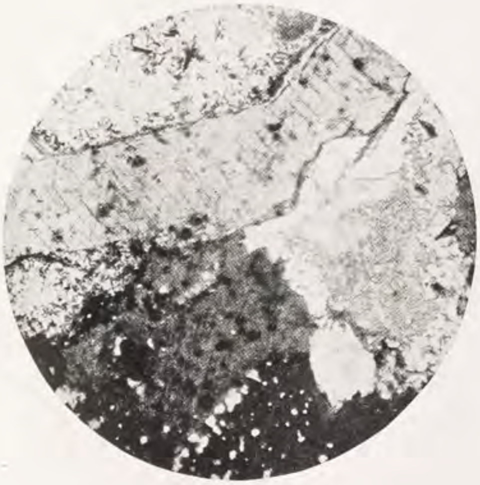


Fig. 3.

Fig. 4.

A. L. HALL PHOT.

PLATE XXXI.

PLATE XXXI.

Fig. 1.

Recrystallised amygdule in metamorphosed Basal Amygdaloid. Boundary between Brakfontein and Rietpoort. The kernel of the amygdule consists of one single quartz-crystal, surrounded by a rim of actinolite interrupted at the top-end by two crystals of zoisite. The rim of amphibole is again encircled by a quartz-mosaic. Magn. 42 ×.

Fig. 2.

Same as Fig. 1. Crossed Nicols.

Fig. 3.

Andalusite-cordierite-biotite-hornfels. Baviaanskrans, Witbank. Cordierite occurs in several large irregular light-coloured areas containing many inclusions of ottrelite and quartz. The ottrelite is often arranged encircling the outline of the cordierite in black wreaths. Biotite is obvious. Magn. 33 ×.

Fig. 1.

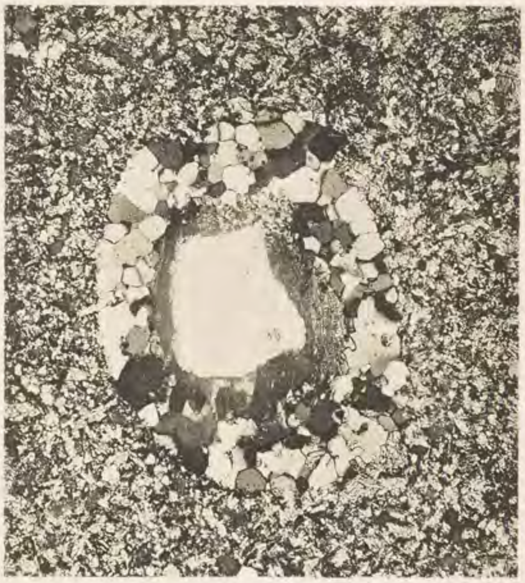


Fig. 2.

P. KRUIZINGA PHOT.

Fig. 3.

A. L. HALL PHOT.

PLATE XXXII.

PLATE XXXII.

Fig. 1.

Basal Amygdaloid, Leeuwdoorns. Prisms and needles of actinolite in epidioritised diabase. In the middle ill-defined amygdules of type I. Magn. 42 ×, Crossed Nicols.

Fig. 2 and 3.

Basal Amygdaloid. Brakfontein-Rietpoort. Amygdule of Type I in epidioritised amygdaloidal diabase. The amygdule is bordered by a faint rim by crowding of crystals of amphibole. Needles of actinolite penetrate into the quartz-mosaic of the amygdule. Magn. 31 ×; Fig. 2. Ord. Light, Fig. 3. Crossed Nicols.

Fig. 1.

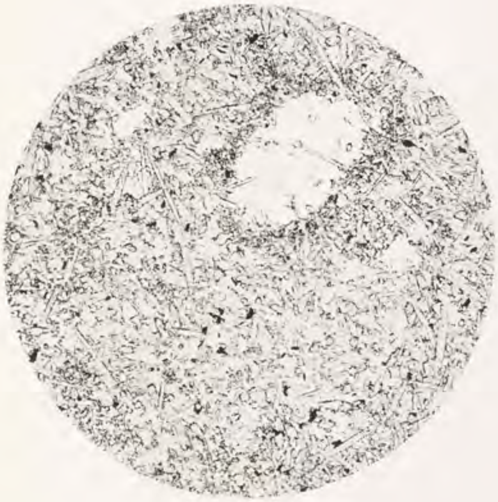


Fig. 2.

Fig. 3.

P. KRUIZINGA PHOT.

PLATE XXXIII.

PLATE XXXIII.

Fig. 1.

Recrystallised amygdule of type II in metamorphosed Basal Amygdaloid. Rietpoort. Actinolite, *a*. apatite, *pl*. plagioclase, *t*. titanite. Magn. 14 ×.

Fig. 2.

One of the amygdules in Fig. 1 seen with crossed nicols, showing the plagioclase.

Fig. 3.

Recrystallised amygdule of type IIIa in metamorphosed Basal Amygdaloid. Brakfontein-Rietpoort. The kernel of the amygdule consists of three quartz-individuals, the interior rim of a quartz-mosaic. Wedged in between the kernel and the rim some actinolite. Magn. 31 ×, Crossed Nicols.

Fig. 1.

Fig. 2.

Fig. 3.

P. KRUIZINGA PHOT.

PLATE XXXIII.

Fig. 1.

Recrystallised amygdule of type II in metamorphosed Basal Amygdaloid. Rietpoort. Actinolite, *a*. apatite, *pl*. plagioclase, *t*. titanite. Magn. 14 ×.

Fig. 2.

One of the amygdules in Fig. 1 seen with crossed nicols, showing the plagioclase.

Fig. 3.

Recrystallised amygdule of type IIIa in metamorphosed Basal Amygdaloid. Brakfontein-Rietpoort. The kernel of the amygdule consists of three quartz-individuals, the interior rim of a quartz-mosaic. Wedged in between the kernel and the rim some actinolite. Magn. 31 ×, Crossed Nicols.

Fig. 1.

Fig. 2.

Fig. 3.

P. KRUIZINGA PHOT.

PLATE XXXIV.

PLATE XXXIV.

Fig. 1.

Recrystallised Basal Amygdaloid. Rietpoort. Type IIIb. The amygdule is surrounded by an exterior rim almost devoid of femic minerals. The outer rim of the amygdule consists almost entirely of quartz; in the interior actinolite is abundant and, besides quartz, apatite in a big lump, and iron-ore are visible. Near the lower edge two small rounded crystals of apatite, one in the exterior rim and the other protruding from the exterior rim into the amygdule. Magn. 31 ×.

Fig. 2.

The same as fig. 1. Crossed Nicols.

Fig. 1.

Fig. 2.

P. KRUIZINGA PHOT.

PLATE XXXV.

PLATE XXXV.

Fig. 1.

Recrystallised Basal Amygdaloid. Type IIIb, Rietpoort East. Around the amygdule the exterior rim devoid of femic minerals is well developed. The amygdule is composed of one single crystal of quartz only, in which some actinolite is enclosed. Magn. 23 ×.

Fig. 2.

The same as fig. 1, Crossed Nicols.

Fig. 1.

Fig. 2.

P. KRUIZINGA PHOT.

PLATE XXXVI.

PLATE XXXVI.

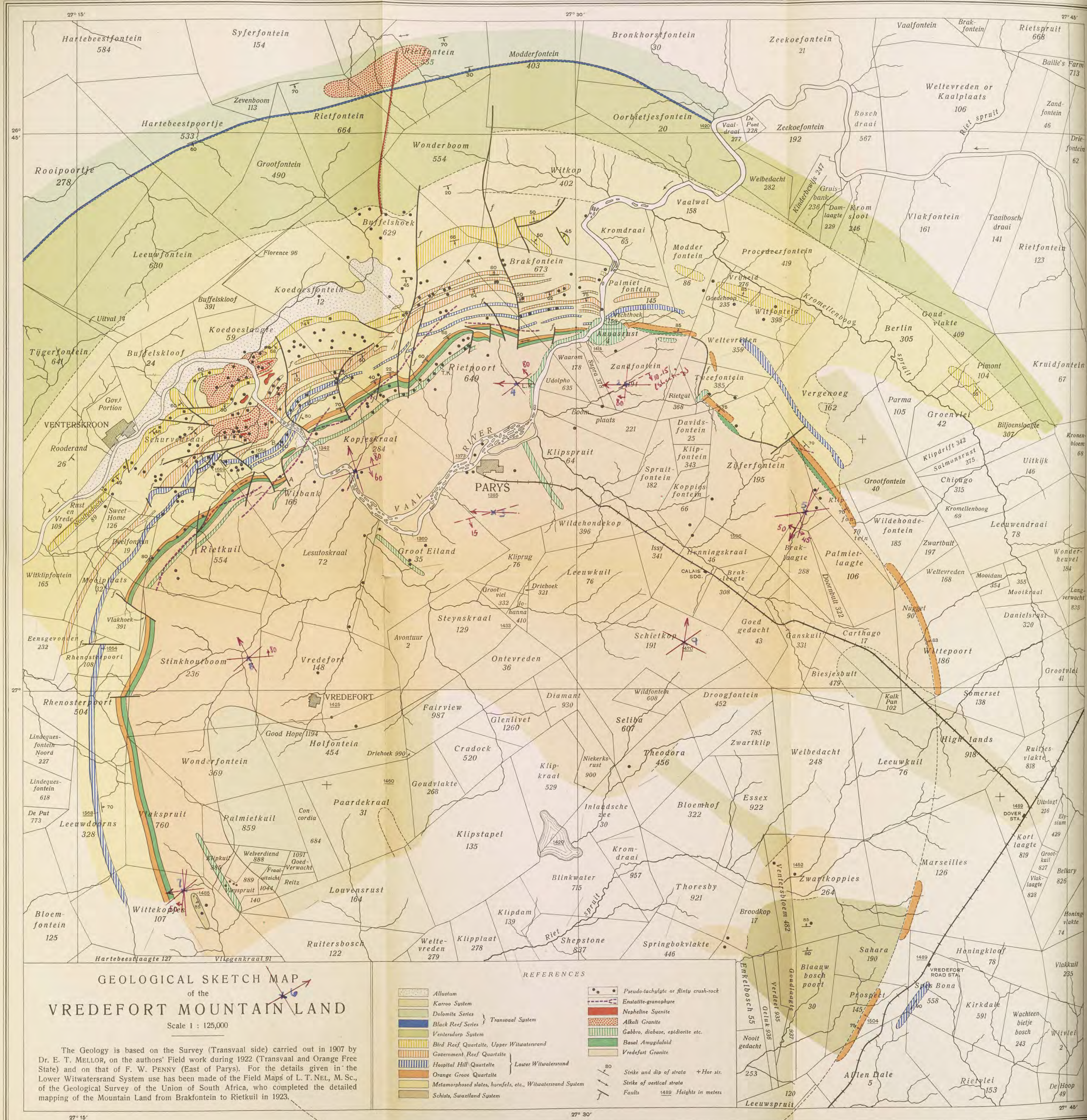
Sketch-map of igneous phenomena along the margin of the north-western section of the Vredefort Granite Boss (after a Survey made by L. T. Nel M. Sc.).

First sheet.

1. Vredefort Granite.
2. Basal Amygdaloid.
3. Blocks of hornfels in Basal Amygdaloid.
4. Orange Grove Quartzites.
5. Gabbro, Hyperite, Epidiorite.
6. Enstatite-Granophyre, e.g.

   f. faults.

Occurrences of pseudo-tachylyte are not marked on this sketch-map.



Lith. N.V. J. Smulders & Co., den Haag

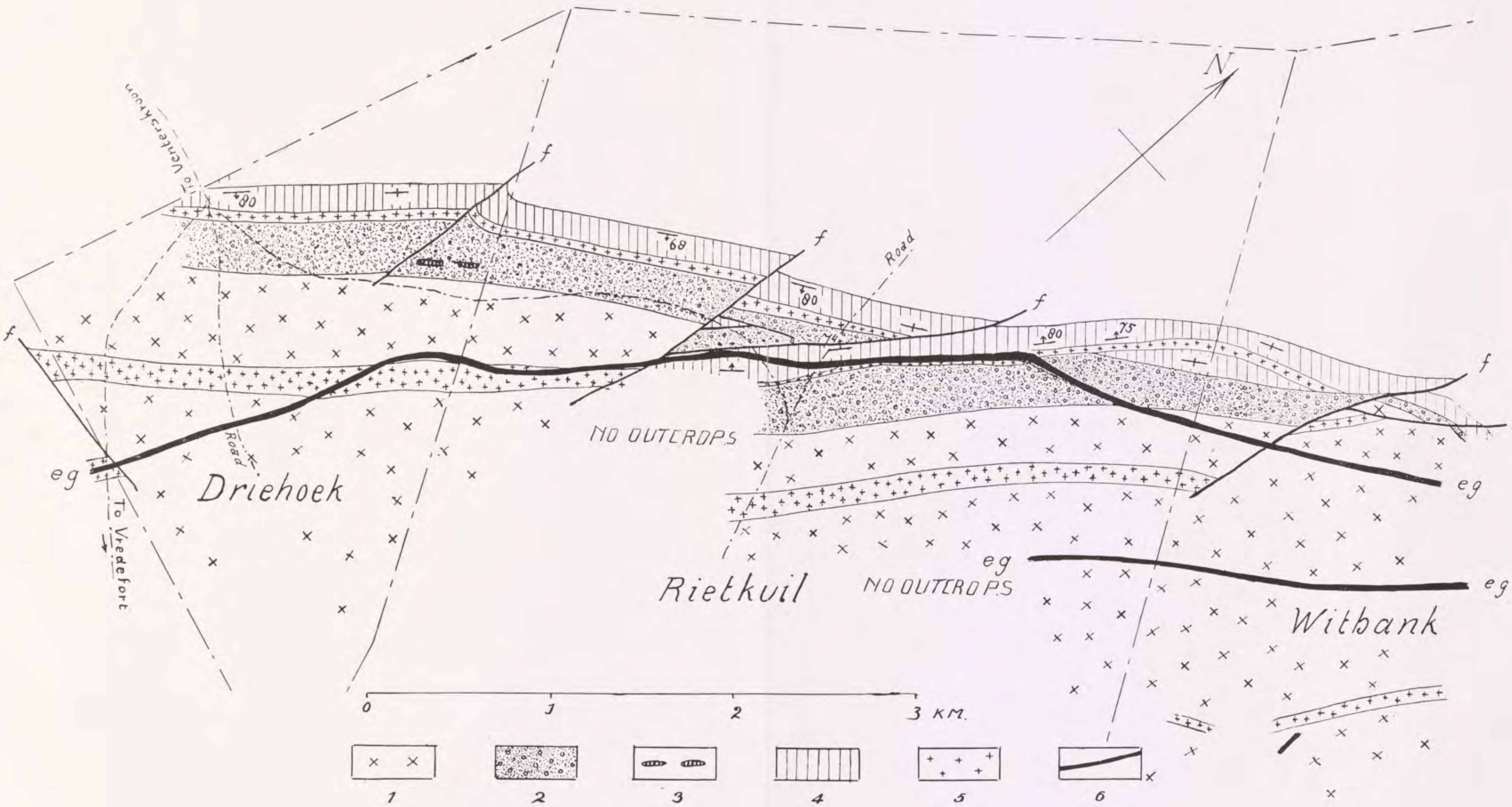

N
To Ventersdorp
f
f
f
f
f
f
Road
Road
80
60
80
80
75
eg
eg
eg
eg
Driehoek
NO OUTCROPS
Rietkuil
NO OUTCROPS
Witbank
To Vredefort
0
1
2
3 KM.
1
2
3
4
5
6

PLATE XXXVII.

PLATE XXXVII.

Sketch-map of igneous phenomena along the margin of the north-western section of the Vredefort Granite Boss (after a Survey made by L. T. Nel M. Sc.).

Second sheet.

1. Alluvium.
2. Government Reef Quartzites.
3. Hospital Hill Quartzites;
   u, upper, *l.* lower.
4. Altered partly ferruginous slates and hornfels.
5. Water Tower Slates: altered ferruginous slates and hornfels.
6. Orange Grove Quartzites.
7. Basal Amygdaloid.
8. Pseudo-tachylyte or flinty crush-rock.
9. Enstatite-granophyre, *eg*.
10. Alkali Granite.
11. Gabbro, Diabase, Epidiorite etc.
12. Vredefort Granite.
    F. Faults.

Dykes of nepheline-syenite are not marked on this sketch-map.

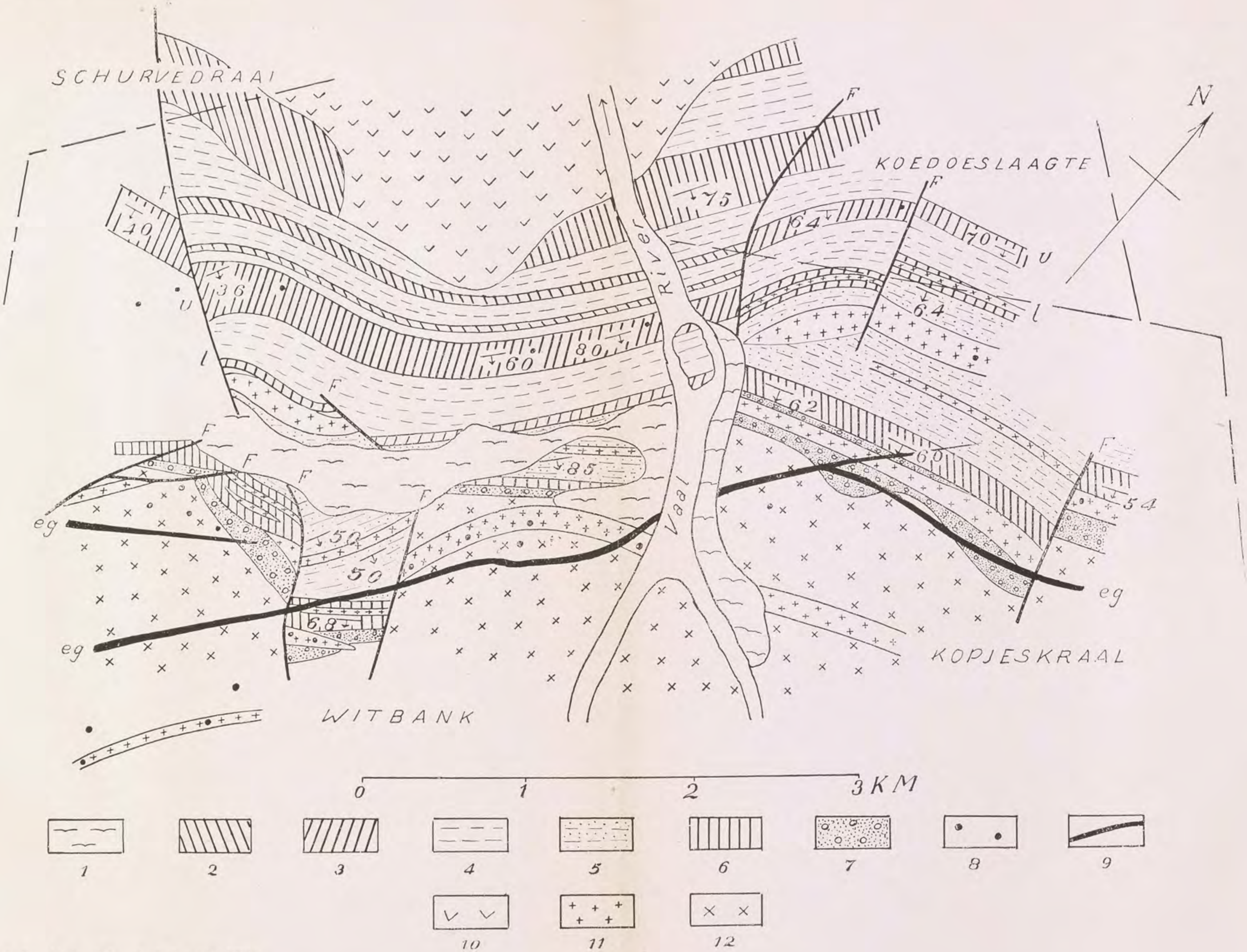

SCHURVEDRAAI
KOEDOESLAAGTE
KOPJESKRAAL
WITBANK
Vaal River
N
F
eg
u
l
0
1
2
3 KM
1
2
3
4
5
6
7
8
9
10
11
12

PLATE XXXVIII.

PLATE XXXVIII.

Sketch-map of igneous phenomena along the margin of the north-western section of the Vredefort Granite Boss (after a Survey made by L. T. Nel M. Sc.).

Third Sheet.

1. Vredefort Granite.
2. Basal Amygdaloid.
3. Orange Grove Quartzites.
4. Gabbro and Epidiorite.
5. Enstatite Granophyre, *eg*.
6. Pseudo-tachylyte or flinty crush-rock.
7. Alluvium.

f. faults.

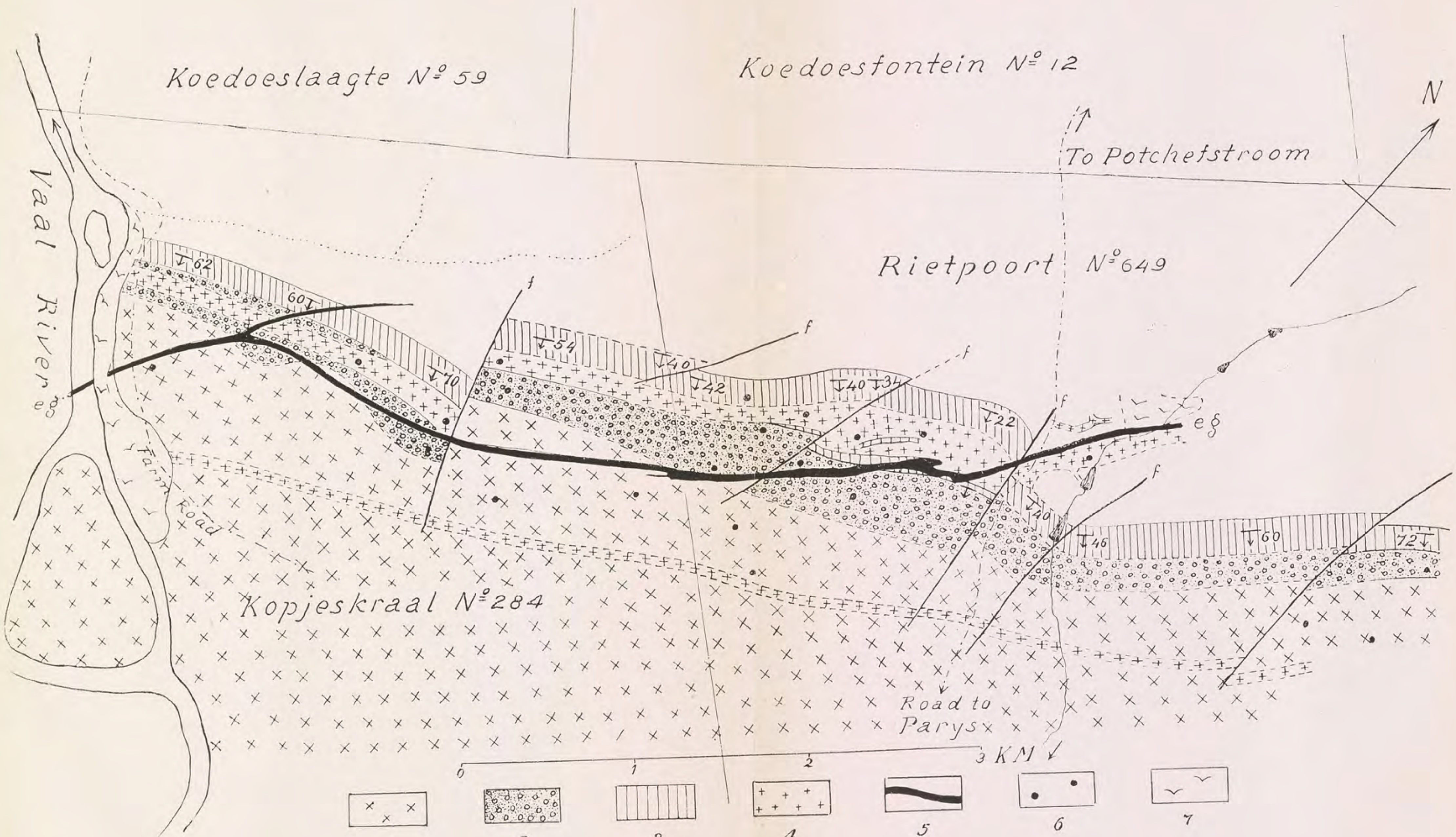
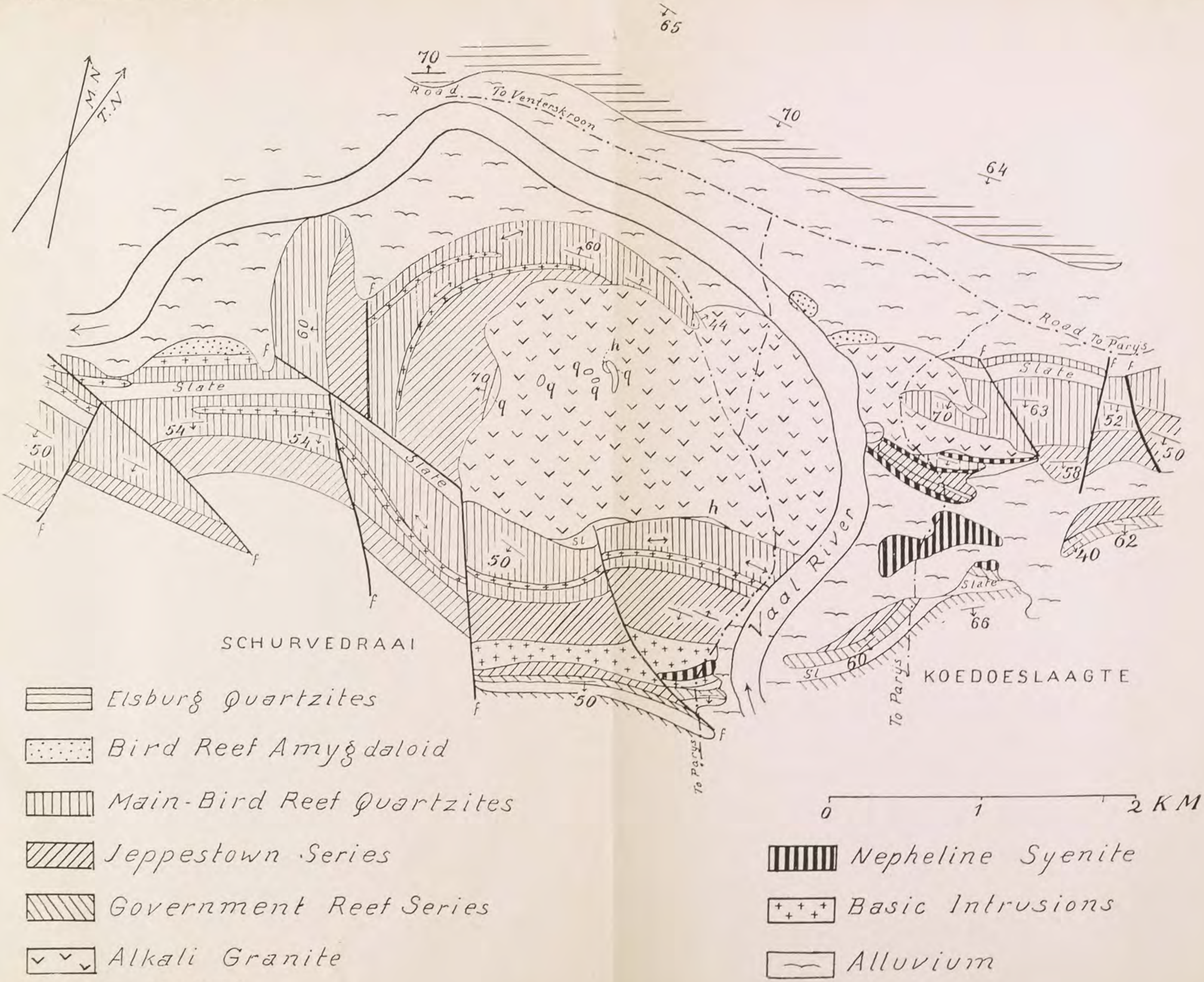

Koedoeslaagte N° 59
Koedoesfontein N° 12
To Potchefstroom
N
Rietpoort N° 649
Vaal River
Farm Road
Kopjeskraal N° 284
Road to Parys
0
1
2
3 KM
1
2
3
4
5
6
7

PLATE XXXIX.

PLATE XXXIX.

Sketch-map of the second boss of alkali-granite and the accompanying dykes of nepheline-syenite on Schurvedraai and Koedoeslaagte (after a Survey made by L. T. Nel M. Sc.).

q. quartzite, *h*. hornfels, *f*. faults.


M.N.
T.N.
Road To Venterskroon
Road To Parys
Slate
Vaal River
SCHURVEDRAAI
KOEDOESLAAGTE
To Parys
0 1 2 KM
Elsburg Quartzites
Bird Reef Amygdaloid
Main-Bird Reef Quartzites
Jeppestown Series
Government Reef Series
Alkali Granite
Nepheline Syenite
Basic Intrusions
Alluvium